

MEASUREMENT OF ABSOLUTE OXYGEN CONCENTRATION BY TUNABLE DIODE LASER ABSORPTION SPECTROSCOPY (TDLAS) IN VERY FINE WATER MIST ENVIRONMENTS

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INTRODUCTION

Water functions as a fire suppression agent through two well known mechanisms: oxygen displacement and reaction zone cooling [1]. In smaller fires, the cooling mechanism can have a larger contribution if the water drops evaporate near the reaction zone. In larger fires the oxygen displacement mechanism dominates since more evaporation occurs away from the fire in the high temperature environment.

Navy research shows that water delivered as a fine mist (or fog) is more effective than sprays in suppressing large scale fires[1, 2]. Fine mists have three distinct advantages. First, the small drop sizes that make up the mist allow the water to reach obstructed fires more easily than larger spray drops. Secondly, the water mist system has a lower water demand than the spray system. Lastly, smaller drops evaporate more rapidly, thus displacing the oxygen more quickly (a 5 μm diameter drop at 300 K in dry air will evaporate in ~ 17 msec).

Unfortunately, creating very small drop sizes ($< 15 \mu\text{m}$) in large quantity is a challenge. In this study a piezoelectric-based ultrasonic mister (Nanomist Systems, LLC, Warner Robins, GA) is used to create a water mist/fog. This mister generates mist that has drop sizes less than 15 μm (D10), which easily evaporate and displace oxygen in the vicinity of the fire. A need is then created to monitor the concentration of oxygen near the fire during the fire suppression test in order to determine the suppression efficiency of the mist.

The Naval Research Laboratory Chesapeake Bay Detachment (NRL-CBD) full scale fire test platform is used to conduct fire suppression tests[3]. At this site two compartments have been built that represent flammable liquid storage rooms (FLSR) on board Navy ships. The smaller 28 m^3 compartment, FLSR1, was used in these studies. The compartment is equipped with instrumentation to monitor a variety of parameters in the test area. There are two separate instruments capable of measuring oxygen concentrations while the various suppression techniques are employed. The first is an extractive sampling line connected to a paramagnetic oxygen analyzer, POA (Rosemount Analytic NGA2000). Concentration determinations will always be too high when sampling in the presence of water (both liquid and vapor) since the

sampled volume of air first has the water removed before the analysis is performed. The second instrument used for monitoring the oxygen concentration in FLSR1 is a zirconia oxygen analyzer, ZOA (ABB model ZMT). The zirconia oxide in this device must be heated to approximately 600 °C for proper operation. The liquid water in the vicinity of the probe will be vaporized. Thus, this instrument will report lower O₂ concentrations in the presence of water drops. The POA has a 60 second lag time in measuring oxygen due to the transport of the extracted air to the analysis region. The ZOA lag time is dependent on sample transport through a protective flash arrestor, and is approximately 60 seconds for its current configuration.

The successful application of tunable diode laser absorption spectroscopy (TDLAS) to monitor molecular oxygen in a water mist suppressed fire environment was reported at this meeting in 2000[4]. The water mist, produced from a high-pressure discharge system, had an average drop diameter of ~ 40 μm. The TDLAS measured oxygen concentrations during water mist suppression tests were compared to the ZOA and POA oxygen measurement techniques[5]. The resulting TDLAS data provided real-time, quantitative oxygen concentrations throughout the duration of the tests, including the times of highest beam attenuation during the water discharge.

The attenuation was greater in the water mist studies than in the water spray studies, an observation attributed in part to the higher number density of the smaller water drops. To decrease the attenuation, the pathlength of the TDLAS spectrometer can be reduced. This is done at the expense of the magnitude of the oxygen absorption feature (as described in Beer's Law). Therefore, a balance must be achieved where the absorption feature is large enough to extract concentration information throughout the tests (where O₂ levels drop as low as 8-12%), while minimizing the attenuation due to the drops.

The purpose of this research is to determine the applicability of the TDLAS approach for measuring oxygen concentrations in the presence of dense, sub 10 μm diameter water drops. In an attempt to quantify the effectiveness of the TDLAS spectrometer in this environment, studies were also performed in well-controlled laboratory experiments to more accurately determine the mist characteristics (drop size, number density, and total mass fraction of water) generated by the misters.

CHARACTERIZATION OF THE MIST

A corral with dimensions of 85 cm x 130 cm x 80 cm (L x W x H), shown in Figure 1, was constructed in the laboratory to contain the mist in order for the characterization of the drops produced by the mister. The mister requires the input of water at the base of the unit, which fills the unit to its operating volume. A drain hole, midway up the unit, prevents over filling and keeps the water level at a constant height above the piezo-elements. A 12-volt 'CPU' fan (5500 mL/s) is used to push air into the mister and transport mist out of the top of the unit, through a dryer hose, into the corral.

On the opposite end of the corral is a dryer hose that is connected to a phase Doppler particle analyzer (PDPA) setup. The top of the PDPA sample container is attached to the main vent line, and the resulting draw is used to pull the mist up from the corral, through the PDPA sample

volume, and out to the vent. A slotted cap was placed on the end of the dryer hose to ensure that the flow of mist into the hose was primarily horizontal in order to minimize vertical mixing. The

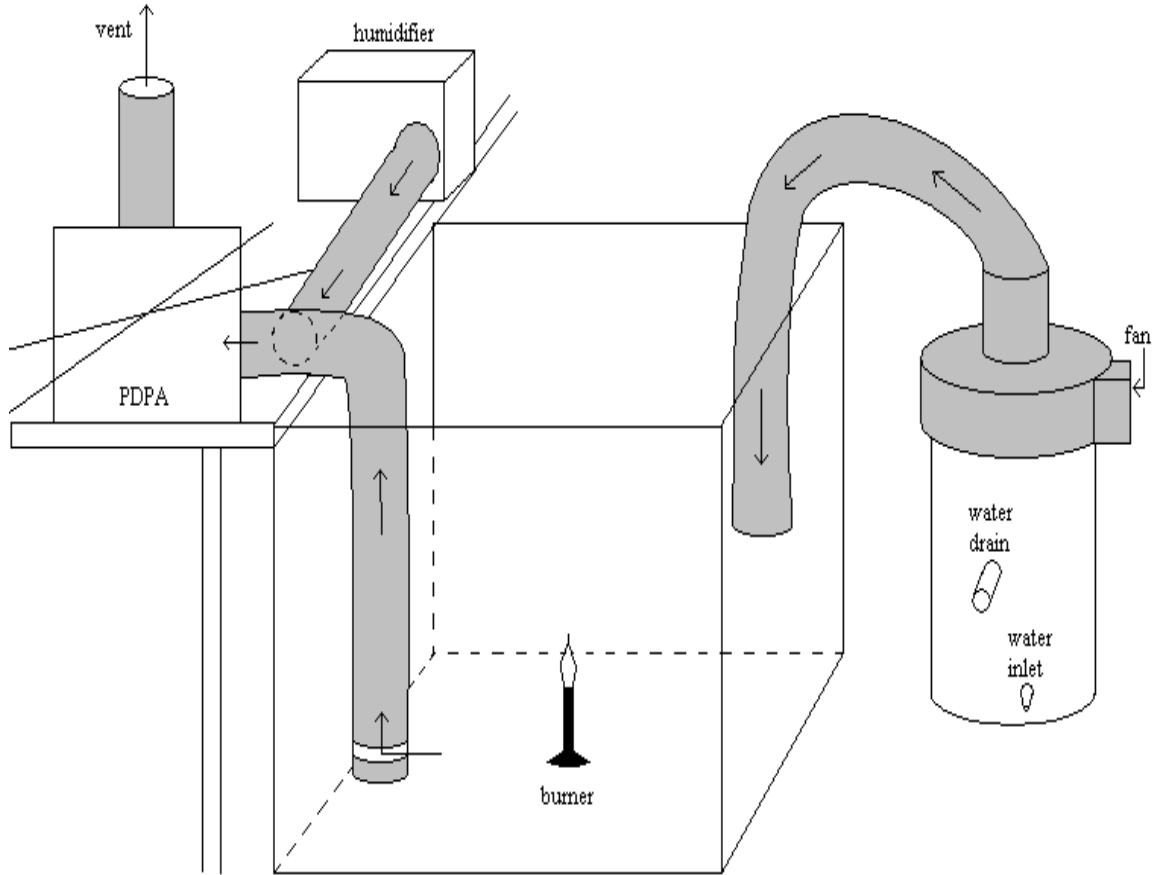


Figure 1. The laboratory experimental setup for the mist drop size characterization using PDPA for mist extracted from the corral. Optical Density Measurements were also made in this configuration by placing the laser and detector in the corral.

mist that is collected in the corral is too dense to be sampled directly by the PDPA (too much laser attenuation by the mist). A dilution line was added that delivered humidified air to the mist inlet hose. Reducing the opening area of the sampling hose compared to the dilution air intake area achieved a dilution of approximately three parts humidified air to one part mist. Several tests were performed to verify that the humidified air (usually 65% relative humidity at 22°C) did not reduce the size of the drops before they reached the PDPA. The volumetric flow from the vent was measured to be about 5400 mL/s. The flows for the humidified air and mist were 3550 mL/s and 1350 mL/s, respectively. The dryer hose seal attached to the PDPA was not airtight and believed to be the cause of the missing 500 mL/s, which reduced the total volumetric flow to the PDPA. The mixing ratio is unaffected by this loss in flow, so the dilution is constant.

The first set of experiments to characterize the mist determined how the drop size of the mist in the corral changed with time. Figure 2 shows mist taken for a period of 250 seconds at the base of the corral. As mist first enters the corral, drops begin evaporating in the relatively dry air before reaching the PDPA measurement volume, resulting in smaller drops. As the mist fills the corral, the measured drop size increases because there is less evaporation of the particles due to the high humidity in the corral. Once the corral filled to its maximum height of approximately 35-45 cm the mist drop size began to level off to an average diameter of at 8 μm , with a Sauter mean diameter (SMD) of 11 μm .

The drop size as a function of height in the mist was also determined. To acquire this data, the inlet to the PDPA was placed at the base of the corral and moved up in the mist for subsequent drop size measurements. Figure 3 shows that at 200 seconds after the mister was initiated, the drop size at the base of the corral is at its minimum (average diameter of 7 μm , 10 μm SMD). The PDPA data shows an increase in diameter from 7 μm up to 10 μm (10 μm to 12 μm SMD). Statistical (1σ) error bars are shown for measurements at 28.9 cm. Above this height the mist began to drift upwards in a non-uniform manner. The drop diameter decreases above 28.9 cm. It is believed that as the drops drift above the bulk mist level the sizes decrease because of evaporation induced by the drier laboratory air above the mist (23 $^{\circ}\text{C}$, 16% relative humidity). It is curious to note that the larger drops are higher in the mist, but overall the drop diameters are fairly constant at about 8 μm ($\pm 1 \mu\text{m}$) throughout the mist.

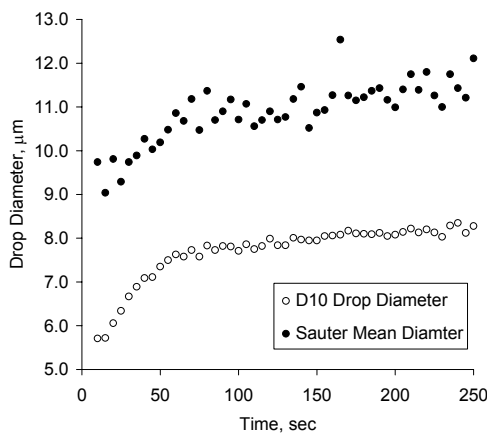


Figure 2. Drop size taken as a function of time at a height of 2.5 cm off the corral floor.

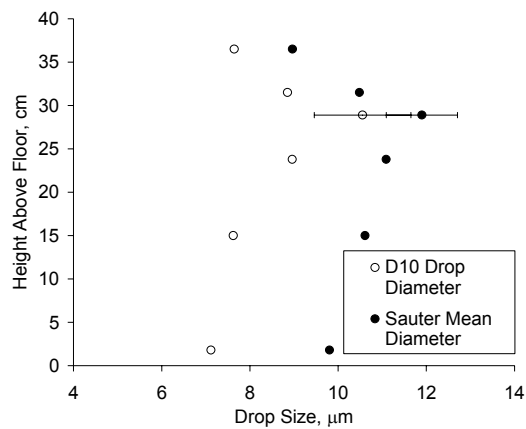


Figure 3. Drop size taken as a function of height in the corral after the mister had been on for 200 seconds. The top of the mist reached a height of about 30 cm in the corral at this time. The corral height was 80 cm.

Optical density measurements (ODM) were investigated to quantify the mass fraction of water. For the ODM, a diode laser operating at 646 nm was directed to a silicon photodiode separated by a known distance. The first step was to check the linearity of the attenuation on mist amount. Mist density was sufficiently high so that multiple scattering must be considered. Light that experiences multiple scattering but still reaches the detector would lead to an extinction coefficient that varies with pathlength. A series of ODM measurements taken with various separation lengths between the source and detector in the mist is shown in Figure 4. The results indicate that this relationship is linear, i.e. a constant extinction coefficient. Thus, the amount of multiple scattered light that reaches the detector is not significant. Another verification that multiple scattering of the light does not effect the ODM measurements was accomplished by

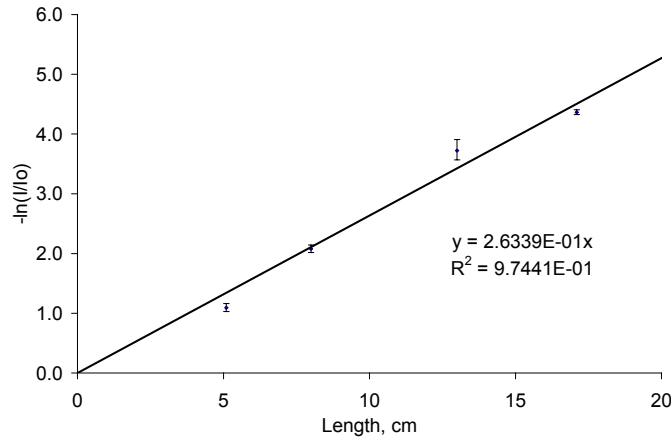


Figure 4. Attenuation versus pathlength using the 642 nm diode laser ODM in the corral containing mist.

placing a polarizer just before the detector. In this experiment the laser used was the 760 nm DFB laser, which produces a polarized beam. The polarizer was oriented perpendicular to the laser beam polarization, and no increase in signal was detected when the mist was present.

A clear plastic tube (inner diameter of 8.7 cm) was attached at the top of the mister. The 646nm diode laser was directed through the mist flow to a detector on the other side. The volumetric flow of air through the mister was measured with a vane anemometer

(Davis DI10570). The mister liquid reservoir run off was monitored in order to determine the amount of water that was leaving the mister as mist. With the mister turned off, the water run off was 289 ± 8 mL/min. After the mister was turned on and allowed to run for a minute, the liquid run off dropped to an average value of 203 ± 8 mL/min. These two numbers indicate a volumetric loss rate of water to mist of 86 mL/min (or 1.44 mL/sec). The airflow at the top of the mister was measured to be 5530 mL/sec, with a temperature of 38 °C. The resulting mass fraction of water (g H₂O/g air) exiting the mister was then calculated to be 19 ± 2 % (or 0.26 g H₂O/L).

This concentration for water was incorporated into Beers law,

$$-\ln\left(\frac{I}{I_o}\right) = a \cdot l \cdot c_{liq-H_2O} \quad (1)$$

where I_o is the intensity before the mist, I is the intensity after passing through the mist, a is the extinction coefficient for water at this wavelength, l is the pathlength and c_{liq-H_2O} is the concentration (g H₂O/L). With a known pathlength of 8.7 cm and the measured intensity loss at the top of the mister, the extinction coefficient could be determined. This calculation is made under the assumption that the drop distribution at the top of the mister is the same as that of the mist that fills the corral. PDPA measurements of drops from both locations showed

similar distributions. The concentration (in units of water mass fraction) can then be calculated since it is the only unknown in Equation 1. The 646 nm diode laser and detector (ODM apparatus) were placed in the corral at a height of 21 cm to monitor attenuation (I/I_0) as the mist was generated.

TUNABLE DIODE LASER ABSORPTION SPECTROSCOPY

Molecular oxygen has an absorption band around 762 nm (13123.4 cm^{-1}), which belongs to a vibrational subtransition of the $b^1\Sigma_g^+ \leftarrow X^3\Sigma_g^-$ magnetic dipole transition[5-7]. The R13Q14 line located at 760.26 nm (13153.4 cm^{-1}) was used to monitor oxygen in this report. This line was chosen because it has one of the higher line strengths of the transitions in this region. This transition has a room-temperature line strength ($T = 296\text{K}$) of $6.302 \times 10^{-24} \text{ cm}^{-1}/\text{molecule cm}^{-2}$ ($1.568 \times 10^{-4} \text{ cm}^{-2} \text{ atm}^{-1}$), and a pressure broadened halfwidth of $5.97 \times 10^{-3} \text{ nm}$ (0.1028 cm^{-1}).

In addition to absolute line strength, another major consideration when selecting a transition to monitor during fire suppression test is how the strength of the transition will vary with temperature. The line strength is governed by the Boltzmann fraction of molecules in the absorbing state, which is dependent on temperature. It is desirable to select a transition that has a minimal change in line strength through the expected temperature range. A compromise must be reached between line strength and line intensity temperature dependence. A maximum line strength is achieved around 200 K for the R13Q14 line. The line strength decreases at an approximate rate of 0.2% per K from 300 K to 500 K. Thus, the favorable line strength temperature dependence led to the selection of this line over transitions that have larger strengths.

The experimental setup for the TDL spectrometer is shown in Figure 5. The diode laser is a distributed feedback (DFB) laser (Sensors Unlimited), centered at 760.5 nm (13149.2 cm^{-1}). The laser is tunable over a few nm by varying the temperature and current applied to the diode. This DFB laser was controlled by a temperature and current module (ILX model LCD3714b). Laser light was detected with a silicon photodiode. The signal was amplified by a variable gain, low noise current amplifier (Femto DLPCA-100 modified for fast response), and stored on a computer equipped with a fast AD card (Datel PCI416 - four AD converters with 2.5 MS/sec). A nitrogen purge line is attached to the spectrometer box to ensure that no oxygen, mist drops, or soot can enter and degrade the optics. The air extracted for the POA is recycled back to the FLSR1 and is used to purge the mirrors that comprise the Herriott cell.

The diode must be rapidly modulated (2 kHz) in order to minimize the two major disturbances that are common in combustion measurements: transmission fluctuations due to soot particles or water droplets entering the absorption path, and non-laser light reaching the detector[5, 8-11]. A function generator (Stanford Research Systems DS345) was used to apply a three volt peak-to-peak triangular waveform to the diode laser driver, corresponding to a peak modulation amplitude of 25.344 mA based on the experimentally derived transfer function of 8.448 mA/V at a 2 kHz modulation frequency. When the DFB temperature was set to 11.8 °C, and the current was set to 22.542 mA, the laser scanned the wavelength about the R13Q14 line as shown in Figure 6.

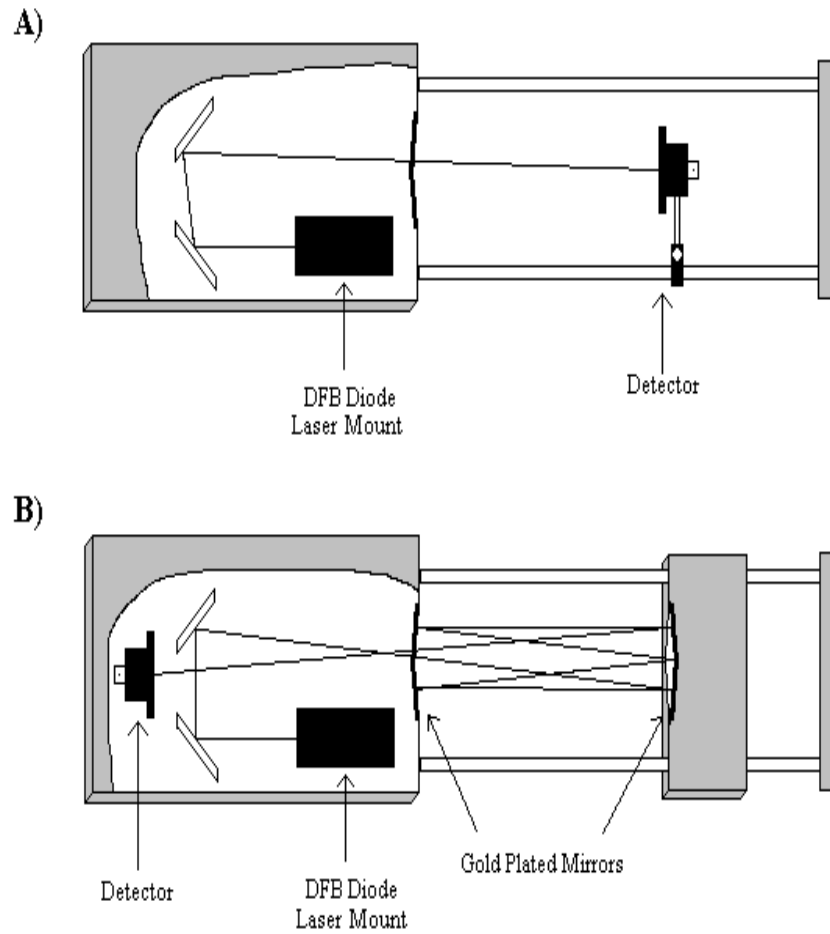


Figure 5. A) Top view of the spectrometer setup with a single pass configuration. B) Top view of the spectrometer with a multi-pass Herriott cell configuration. In both setups, the purge lines to keep the internal optics and gold plated mirrors free of soot and water are not shown.

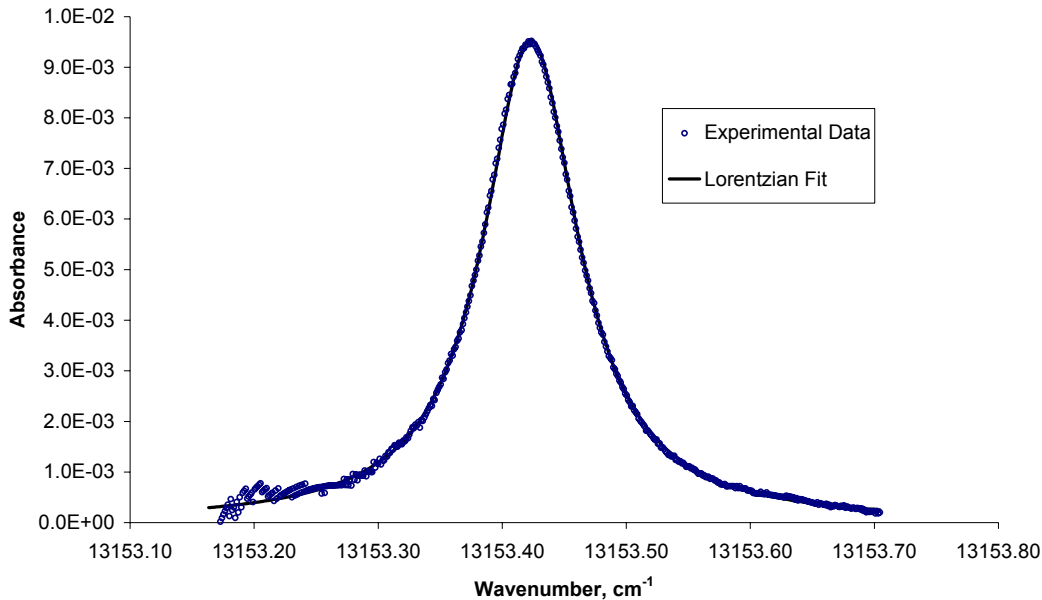


Figure 6. Spectrum of the R13Q14 line used to monitor the molecular oxygen concentration during the fire suppression test. This spectrum was captured during a fire test before the mist suppression was started. The temperature was 17.1 °C and the pathlength of the spectrometer was 48.3 cm. The fit was provided by the data processing Labview software used to calculate the area of the peak.

Wavelength scans were recorded with a custom designed Labview program[4, 5, 8-11] and subsequently stored to the hard drive. Each saved spectrum was the average of 100 to 1000 scans as determined by software. The stored data was post-processed with a second specially developed Labview program[12]. The data processing program identifies the oxygen absorption feature, compensates for disturbances, and extracts the area of the absorption line. To extract the absorption line area and simultaneously correct for transmission/emission fluctuations we used a Levenberg-Marquart-Algorithm with approximated Voigt line shapes and background polynomials up to 3rd order. Line areas were converted into concentrations applying the extended Beer's Law, the ideal gas law and taking into account the dynamic tuning coefficient of the laser and the process gas temperatures measured with thermocouples. With this information it is possible to determine absolute oxygen concentrations without the need for any calibration procedure.

For a given O₂ mole fraction, the magnitude of the absorption feature (area) is dependent on the pathlength of the spectrometer. The longer the pathlength, the lower the detection limit of oxygen obtained with this setup. In the experiments presented here, the pathlength was varied in order to find the optimum length to use. In previous experiments the path was set to 1.47 m [4] and 1.8 m [5] by using an open-path Herriott configuration. These lengths result in a relatively large absorption feature, thus improving the detection limit of the spectrometer. However, in the current experiments with the ultrasonic mister, the attenuation was too great at the maximum mist density encountered to use such long pathlengths. Pathlengths used to acquire data were chosen in attempt to find a balance between detection of oxygen throughout the fire suppression test, and minimizing intensity loss due to beam scatter.

Studies have shown that localized oxygen concentration can drop to as low as 8% in FLSR1

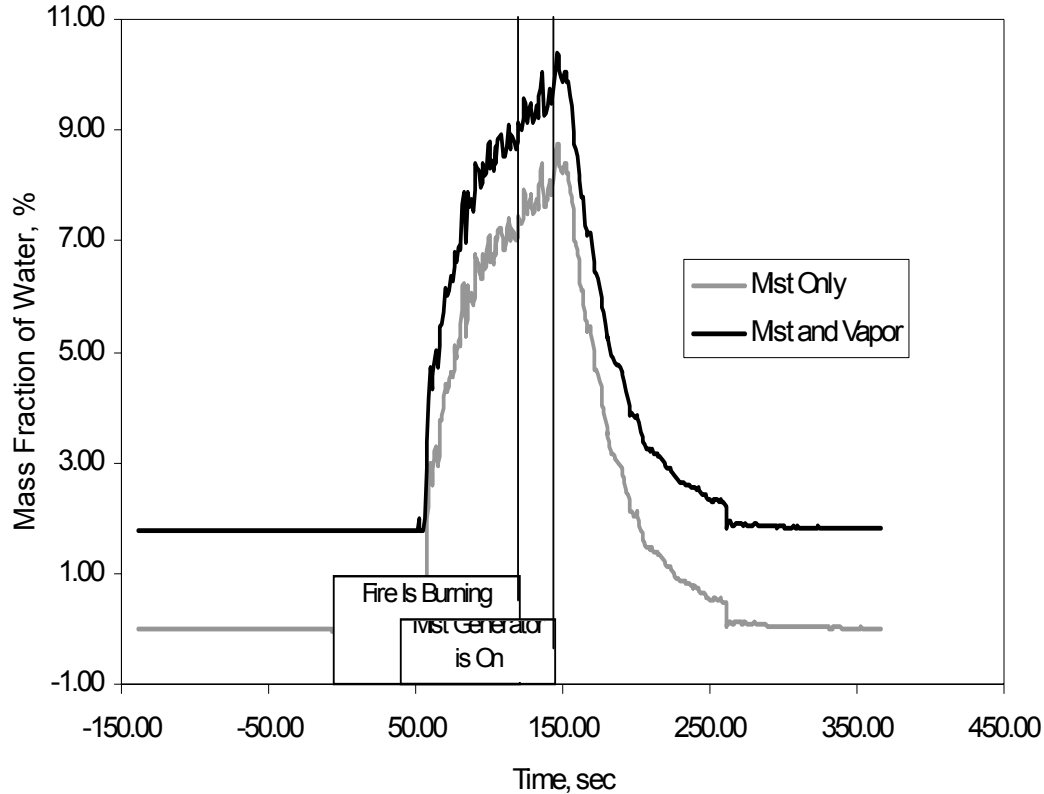


Figure 7. Water mass fraction from mist only taken with the 646 nm diode laser ODM setup in the corral with a small propane flame present. The propane flame extinguished when the liquid water mass fraction was ~8.0 %. The contribution to water mass fraction from water vapor is 1.8 % at 23 °C, and is shown as the darker trace.

during a fire. A pathlength of 5 cm is necessary to measure O_2 concentrations at this level ($S/N = 3$) under laboratory conditions (no fire or suppression present). In a fire, the attenuation that accompanies an O_2 drop to 8% will result in more noise in the absorption scan, and require a longer path to maintain at least a S/N of 3. During the CBD fire suppression test detailed below, pathlengths of 183 cm, 48.3 cm, 36.8 cm, and 26.7 cm were used. The corresponding peak absorption for 21% O_2 at 296 K and 1 atm for the R13Q14 line are 3.7 %, 0.94 %, 0.74 %, and 0.54 % respectively. In laboratory mist laden experiments the pathlength was reduced to as short as 13 cm resulting in an absorption of 0.25 %.

RESULTS AND DISCUSSION

FIRE EXTINCTION STUDIES: LABORATORY

A small Bunsen flame with a one cm inner tube diameter generated with a propane flow of 0.35 standard liters per minute (SPLM) was placed in the corral with the ODM apparatus. Figure 7 shows the mist only water mass fraction as the mist is used to put out the fire. The fire is extinguished when the water drop mass fraction reaches 7.5 %. However, the amount of water vapor present with the mist should also be taken into account. Air saturated with water vapor at 23 °C has an absolute water vapor mass fraction of 1.8 % (in the absence of mist). Adding the water vapor to the calculation of mist water mass fraction results in a total water mass fraction of 9.1 % at the time the fire went out.

Sheinson *et al* developed a model based on extensive cup burner data, which predicts 14 molar percent of liquid water, or 24 molar percent of water vapor to extinguish a heptane flame via a thermal mechanism[13]. The work described by Hamins *et al* indicates that flames fueled by either propane or heptane require approximately the same amount of suppression agent to extinguish[14]. Based on these findings, it is assumed that the similar amounts of water are

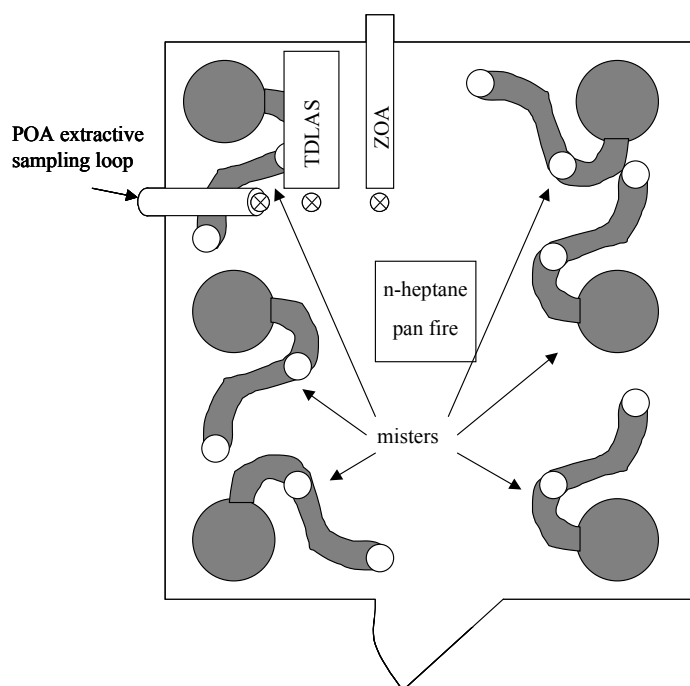


Figure 8. Top view of FLSR1 showing the location of 6 mister units along the perimeter of the room, extraction position for the POA sampling loop, and measurement positions for the ZOA detector and TDLAS. Each mister has two outlets in the duct work for mist to escape into the room. There was 750 mL of n-heptane fuel in the pan.

required to extinguish heptane or propane flames. This assumption allows for the ODM water mass fraction obtained extinguishing a propane flame to be compared with reported literature values for heptane flames.

30 molar percent of N_2 added to one liter of air increases the heat capacity of the air by 0.56 kJ. This amount of N_2 is required to extinguish a propane fire[13,15]. The 7.5 ± 0.8 % mass fraction obtained from the ODM measurement is due to the presence of water drops, and is equivalent to 11 ± 1 molar percent. This molar percentage increases the heat capacity of the air by 0.47 ± 0.5 kJ. The water vapor that is present (2 molar percent) will increase it another 0.05 kJ, bringing the total to 0.52 kJ. There is a 7% difference compared to the required 0.56 kJ predicted, which is within the uncertainty of the ODM.

This is further validation of the ODM mass fraction values.

FIRE EXTINCTION STUDIES: FIELD TESTS

The test scenarios that took place at the Chesapeake Bay Detachment all incorporated a 12" x 12" n-heptane pan fire located in the center of FLSR1. The height of the pan was 32 cm above the floor. The ZOA, POA, and TDLAS spectrometer measurement locations were all located at 46 cm above the floor. As shown in Figure 8, The ZOA was closest to the pan fire at 67 cm, followed by the TDLAS at 78 cm, and then the extractive sampling tube leading to the POA was located at a distance 98 cm from the center of the fire pan. The mist suppression system included six individual units that were spaced about the room, with each mister having two openings to release the mist.

The first experiments in the present study used a previous setup in Herriott configuration with a pathlength of 180 cm [4, 5]. Due to the severe scattering and absorption losses caused by the much finer mist, the initial Herriott-based TDLAS setup was unable to determine oxygen concentrations with sufficient resolution once the mist reached the TDLAS spectrometer measurement volume. This was attributed to the much higher scattering coefficients of the fine mist. We converted the TDLAS setup to a single pass configuration thereby reducing the pathlength to 36.8 cm. This drastically reduced the scattering losses at the expense of the oxygen

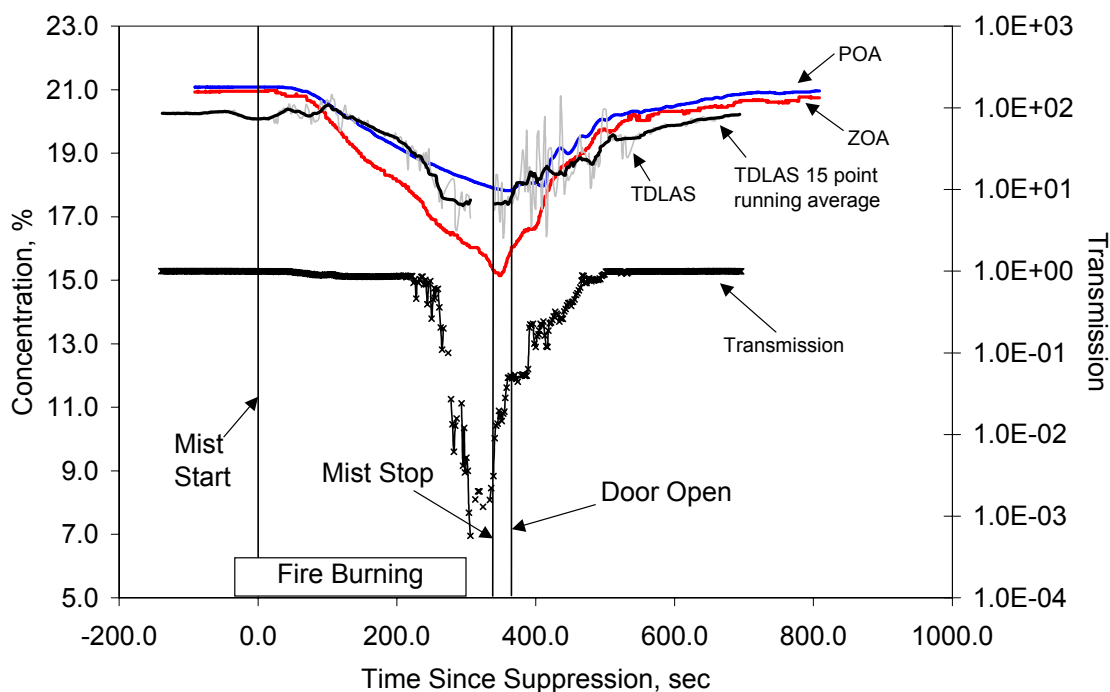


Figure 9. Data taken during CBD fire suppression with the single pass TDLAS setup in FLSR1. The pathlength of the spectrometer was 36.8 cm. The TDLAS oxygen determination became less reliable and eventually unusable as the transmission signal drops.

absorption signal.

Figure 9 shows TDLAS data captured with a pathlength of 36.8 cm, and ZOA and the POA data during a fire suppression test. The uncertainty in the ZOA and POA measurement values are 0.4 Vol.-% of O_2 and 0.5 Vol.-% of O_2 , respectively. The lighter TDLAS trace in Figure 9 is the oxygen concentration determined from the average of 500 individual scans across the absorption

feature. The darker TDLAS trace is the moving average with an averaging window of 15 concentration values. All oxygen values were obtained without any calibrations procedures, only by use of the spectroscopic parameters of O₂ and the measurements of pressure, temperature, pathlength and the tuning coefficient. An evaluation of the fit residuals of the absorption scans revealed the optical resolution of the spectrometer. Noise sources included detector noise plus AD-converter non-linearities, so that the signal detectivity ($\Delta I_{\min}/I_0$) depended on the amount of light reaching the detector and thus on the transmission of the measurement path. The 1σ detection limit at the start of the experiment for the 38 cm path was $1.1 \cdot 10^{-4}$ OD corresponding to 0.28 Vol.-% of O₂. The increase in scattering losses by about a factor of 500 increased the limit to $1.3 \cdot 10^{-3}$ OD representing 1.65 Vol.-% of O₂. These results clearly imply that the detectivity may be improved by lasers with higher output power. Higher powered lasers would also allow an increase of the absorption pathlength, which would improve the measurement capability. Further enhancement may be attained using a digital signal processor (DSP) to achieve higher data throughput than the conventional DAQ-card computer driven system.

The data presented in Figure 9 does accurately represent the visible observations made during the fire suppression tests. As was mentioned above, the height of the TDLAS spectrometer is about 14 cm above the pan. The mist is generated and released into FLSR1 from the ground and begins to 'fill' the room. It was observed that once the mist reached the level of the fire, its ascent in the room halted. It is speculated that, since the fire is increasing the air temperature above the pan, when the mist reaches this pan level the increase in evaporation losses prevents the mist from continuing to fill the room although the vapor does. In figure 9, the transmission of the TDLAS validates the above mentioned observations, in that the transmission is relatively high upto the time just prior to when the fire goes out and the mist drifts up into the TDLAS sample volume. With a relatively high transmission, the decrease in oxygen concentration for the first 150 seconds of the suppression test is clearly detectable. After the mist puts out the fire, the mist level in the room rises and this TDLAS configuration could no longer monitor oxygen concentrations due to the drastic increase in scattering losses.

A few conclusions can be made when comparing the TDLAS oxygen concentrations to those of the ZOA and POA sensors in Figure 9. The TDLAS has less uncertainty during the measurement time before the fire is extinguished. During this time period the TDLAS O₂ values are higher than the ZOA measurements. This is consistent with the evaporation of water drops in the ZOA measurement volume displacing oxygen. The TDLAS values should be lower than the POA values since all water is removed before the air is analyzed, but at times this is not the case. It is possible that the lag time associated with the dry air purge of the mirrors is returning air that was extracted at a higher oxygen concentration. The presence of this air purge may be responsible for the higher TDLAS O₂ readings before the fire is out, and the lower O₂ concentrations during the period after the fire is extinguished.

The maximum temperature measured in FLSR1 during this burn was 23 °C. If 100% relative humidity was achieved at this temperature, the oxygen concentration would drop from 21% down to 20%. Figure 9 then indicates that the majority of the oxygen loss during the burn is due to the consumption of oxygen by the fire.

CONCLUSIONS

This paper reports the application of TDLAS to measure molecular oxygen in the presence of a very dense water mist generated by piezoelectric-based ultrasonic misters. The high drop number density and low drop size associated with these misters make them attractive for fire suppression. The TDLAS spectrometer used in less challenging water mist environments must then be adapted to compensate for the large attenuation factor associated with the mist from the ultrasonic misters.

A PDPA was used to monitor the mist drop size as a function of residence time, and height in a test-scale corral. The data indicates that the mist has an average diameter of $8 \pm 1 \mu\text{m}$. The largest deviation in drop size is found when the mist interacts with the dry lab air and can be attributed to the partial evaporation of the drops. Despite the high drop number density and multiple scattering, quantification of the mist using an ODM was possible. The ODM was used in the corral during mist suppression of a propane flame. The data were compared with the water concentrations required to extinguish this flame type, and were found to be consistent with the calculated values.

The tunable diode laser based spectrometer was used to monitor oxygen concentrations during the suppression of pan fires in a full-scale suppression test at CBD. The data collected indicate that TDLAS provides more valid concentration values than a paramagnetic or zirconia-based oxygen analyzer due to its ability to measure O_2 in a water-laden environment. However, using a preliminary single path version of the TDLAS spectrometer with a 36.8 cm pathlength, oxygen concentrations could only be detected reliably during low attenuation. Even with this attenuation limitation, TDLAS was able to monitor O_2 concentrations during the suppression of a pan fire up to 30-45 seconds prior to the time the fire was extinguished.

Our previous studies report TDLAS to monitor oxygen concentrations during large scale fire suppression used mist that had a drop size greater than $100 \mu\text{m}$ [5] with a number density of approximately 10^4 cm^{-3} . The piezoelectric-based ultrasonic misters used here were shown to have smaller drops and a higher number density of 10^6 cm^{-3} . The 3 mW laser diode was insufficient to provide enough photons above the detector background noise during times of maximum mist density. It is estimated from our measurements that a diode laser operating with an order of magnitude more power ($\sim 30 \text{ mW}$) could be used with a spectrometer pathlength of 16 cm to monitor O_2 down to 8% in this suppression environment. With this setup, even at the highest attenuation, the R13Q14 O_2 absorption feature would be obtained with a signal to noise ≥ 3 . The industry standard for a 760 nm DFB diode laser in 1999 had a power on the order of a few mW. Recent advances in technology have resulted in a dramatic increase in power for this wavelength region. High power DFB diode lasers ($>30 \text{ mW}$ at 760 nm) are now reported to be commercially available. Future work will incorporate such high-powered DFB lasers into the spectrometer. Further improvements should be possible with a fast DSP-based data acquisition developed recently, which is able to ensure 100% data throughput and thus offers a factor of 3 to 10 resolution improvement compared to a comparable PC-based system with plug-in DAQ cards.

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