

## “A Tunable Diode Laser Absorption Diagnostic for Studying the Fire Suppression Mechanism of Aqueous High Expansion Foams”

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### Introduction

The U.S. Navy is interested in the use of High Expansion (HiEx) foams for protection of large spaces including hangar bays and crowded areas including stowage compartments and engine rooms on naval ships [1]. In general, aqueous HiEx foam consists primarily of air, less than 1% water, and a small amount of surfactant and is generated using proportioning equipment and fans or compressed gas to aspirate the foam. HiEx foams can ‘pile up’, quickly filling a room and getting water to fires located high in the threat space. HiEx foams are highly effective for suppressing fires, but most importantly their use decreases the need for firefighters in the vicinity of the fire, thus risking fewer human lives.

Although the overall HiEx foam fire suppression mechanism is unknown, three mechanisms have been suggested based on empirical understanding [2]. Water contained in the foam evaporates as it interacts with a flame, resulting in (1) heat absorption and (2) dilution of oxygen. Also, the foam may present (3) a physical barrier between the oxygen supply and the flame, thus suffocating the fire; however, air-filled bubbles in the foam that burst will release oxygen to the fire. Because there is very little quantitative data in the literature detailing the interaction of foams with fires, diagnostic methods are needed to monitor combustion gases and temperature during the fire suppression event. In particular, oxygen monitoring will provide valuable information about the competition between the rate of oxygen consumption by the fire and the rate of oxygen release from the foam during a foam-suppressed fire event. Further, quantitative knowledge of the foam-fire interaction can lead to validating modeling predictions, understanding the overall foam suppression mechanism, and optimizing foam use. The goal of this work is to develop a diagnostic to obtain simultaneous measurements of oxygen, water vapor, and temperature through a moving HiEx foam with temporally varying transmission due to refraction and scattering.

### Technique

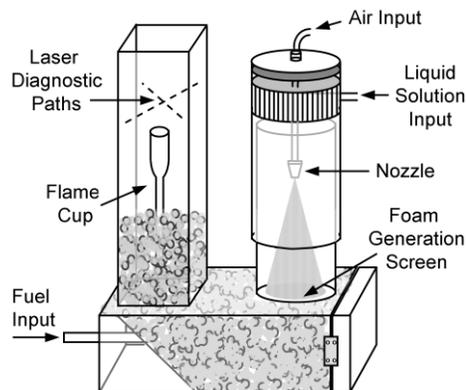
To obtain non-intrusive, *in-situ* gas measurements through moving HiEx foam, we used direct-Tunable Diode Laser Absorption Spectroscopy (direct-TDLAS) to monitor the non-scattered, non-refracted light through the medium coupled with real-time gain amplification to compensate for large transmission fluctuations. Direct-TDLAS, pioneered by Ebert and co-workers, is an optical absorption technique that permits calibration-free measurements of absolute absorber concentrations and gas temperature [3]. The experimental setup consists of a diode laser beam passing through the measurement volume (HiEx foam) to a photodetector. The laser is continuously and repetitively tuned over the target absorption line by linear laser current modulation and species concentration is directly related to the area under the absorption line. Temperature along the laser line-of-sight can be measured rapidly and non-intrusively using two-line thermometry [4]. This technique involves monitoring the ratio of the integrated areas of two

- [1] I. Wilder, *Fire Technology* 5 (1) (1969) 25-37.
- [2] R. Ananth, J. P. Farley, *Journal of Fire Sciences*, *in press* (2009) DOI: 10.1177/0734904109341030.
- [3] H. Teichert, T. Fernholz, V. Ebert, *Applied Optics* 42 (12) (2003) 2043-2051.

transitions with different temperature-dependent line strengths. Direct-TDLAS has been demonstrated by Awtry, *et al.* to monitor oxygen, carbon dioxide, water vapor, and liquid water in an optically dense, highly scattering water mist fire-suppressed environment [5].

### Experimental

Aqueous HiEx foam was generated using a small-scale foam generator integrated with a cup burner apparatus [6]. The modified cup burner apparatus, shown schematically in Figure 1, allows examination of the dynamics of the foam and flame interaction. Air enters the top of a cylindrical acrylic tube (28.5-cm long, 7.6-cm diameter ID) through a perforated plate and is further conditioned using a bed of tightly packed straws (6-cm long). Liquid foam solution (2.2% Buckeye High Expansion Foam and 97.8% water) flow is controlled using a pressurized liquid delivery system and enters the foam generator from the side of the cylinder and out through a nozzle (Model 302-C fine cone, SureShotSprayer.com). The cone spray pattern covers a 6.4-cm diameter copper mesh screen at the bottom of the tube held in place with a rubber gasket. A second cylindrical acrylic tube (16.5-cm long, 7.6-cm diameter ID) is nested inside the outer tube to allow adjustment of the distance from the nozzle to the foam generation screen. This distance is fixed so the liquid spray covers the entire screen while air flows through the screen to generate foam. The foam travels through the lower horizontal aluminum channel (27-cm long, 9.3-cm x 9.3-cm, ID) and into the vertical rectangular quartz channel (43-cm long, 9.9-cm x 9.9-cm, ID) assisted by a 45° ramp to direct foam movement.



**Figure 1: Schematic of the integrated HiEx foam generator/cup burner apparatus**

In these experiments, foam with approximately 100:1 expansion ratio was used, where expansion ratio is defined as the volume of expanded foam to the volume of liquid used to create foam. The foam was generated with a total air flow of 8 L/min resulting in an air flow velocity of 1.3 cm/sec above the cup. Foam moves at ~ 0.5 cm/sec vertically in the channel. Two diode lasers, used to detect water vapor and oxygen absorption lines, are sent horizontally through the vertical cup burner channel at an approximate 32° angle of incidence as shown in Figure 1. While the foam is travelling through the laser paths, transmission fluctuates rapidly by four orders of magnitude due to changes in refraction of the laser beam through the moving bubble surfaces.

### Results and Discussion

Oxygen, water vapor, and laser transmittance were monitored simultaneously as aqueous HiEx foam was generated, traveled through the horizontal channel, then vertically into the cup burner chimney through the laser paths, as shown in Figure 1. Concentrations are shown in the top plot of Figure 2 while transmittance data are shown in the middle and bottom plots. The black line through the oxygen concentration data is a 20-point moving average.

- [4] X. Liu, *Line-of-sight Absorption of H<sub>2</sub>O Vapor: Gas Temperature Sensing in Uniform and Non-Uniform Flows*, PhD thesis, Stanford University, California, USA, 2006.
- [5] A. R. Awtry, B. T. Fisher, R. A. Moffatt, V. Ebert, J. W. Fleming, *Proc. Combust. Inst.* 31 (2007) 799-806.
- [6] J. W. Fleming, R. S. Sheinson, *Fire Technology*, *in press* (2010) DOI: 10.1007/S10694-009-0137-1

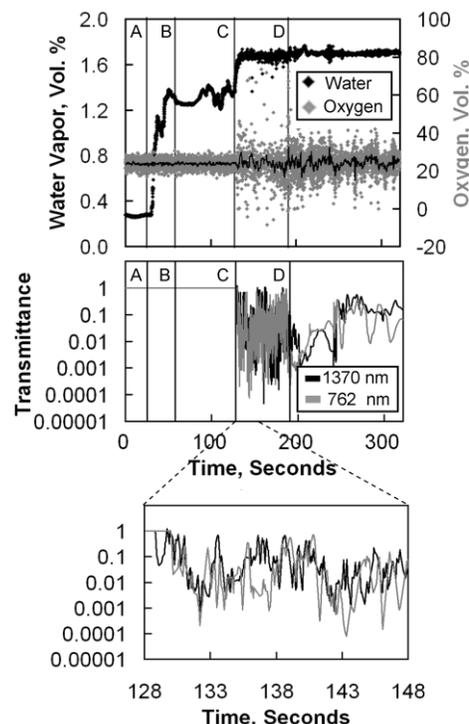
The co-flow air is turned on with a flow rate of 8 L/min through the apparatus and background concentration data were collected with the lasers sampling the chamber at ambient conditions for 25 seconds. At 25 seconds (Figure 2 label A), the liquid solution is turned on with a flow rate of 35 mL/min and sprays on the foam generation screen. The screen is primed for about 30 seconds by evenly distributing the liquid solution on the screen using two fingers, generating foam at 58 seconds (Figure 2 label B). The foam travels horizontally in the lower channel with the co-flow air, then vertically through the cup burner chimney. At 128 seconds (Figure 2 label C), the top layer of foam passes through the laser paths. The foam continues to travel up the chimney causing large, rapid fluctuations in laser transmittance (middle plot of Figure 2) due to changes in refraction through the bubbles as the foam moves through the laser paths. The air and liquid flow are shut off at 191 seconds, stopping foam generation and travel (Figure 2 label D). The bottom plot of Figure 2 shows a detailed section of laser transmittance as the foam is travelling through the laser paths. This plot shows that the transmittance changes by four orders of magnitude while the foam is moving up the cup burner chimney. Temperature was not monitored during this test because it was constant through the foam in the absence of a flame. However, the temperature will fluctuate while HiEx foam is interacting with a flame and will be monitored using two-line thermometry.

### Conclusion

We successfully demonstrated the use of direct-Tunable Diode Laser Absorption Spectroscopy to monitor oxygen and water vapor through highly scattering aqueous HiEx foam. Transmission losses varied by four orders of magnitude with time due to injection of a 100:1 expansion ratio foam into a test chamber followed by foam movement, evaporation, liquid drainage, and scattering/refraction of the laser through the moving bubble surfaces in the foam. Despite rapidly changing transmission over four orders of magnitude, we simultaneously measured molecular oxygen, water vapor, and transmittance throughout the foam injection event. The results indicate that application of this diagnostic technique is possible for non-intrusive, *in-situ* monitoring of combustion species during a High Expansion foam suppressed fire event. Direct-TDLAS coupled with temperature measurements using the two-line thermometry technique will provide valuable quantitative information about the foam/flame interaction. Further, this diagnostic will contribute to our understanding of the overall suppression mechanism and the development and validation of foam/flame modeling predictions.

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**Figure 2: Water vapor and oxygen concentration measurements (top) and laser transmittance (middle and bottom) as foam is generated, moved into the cup burner channel and through the laser paths. Labeled events are as follows: A: liquid on, B: foam generated, C: foam enters laser paths, D: foam generation stops**