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Scope

This Instruction covers the use, design and specifications of optical density meters (ODMs) for smoke measurement in the Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF) Fire Research Laboratory (FRL).

Instrument Description

GENERAL

Smoke measurements in fires are performed for a variety of reasons including toxicity assessment, visibility calculation, and model validation. Measurements are inherently difficult to perform in high temperature environments due to instrument limitations; however smoke data can be obtained downstream of a fire where reduced temperatures allow for use of sensitive instruments. The ATF FRL uses optical density meters to perform smoke measurements; these allow for good time resolution, they can be performed non-intrusively, and are not as labor intensive relative to other smoke measurement techniques.

OPERATING PRINCIPLE

Fires generate a range of products including gaseous species, aerosols and particulates. Optical smoke measurements are based on the attenuation of light as it passes through a particulate and gaseous medium. Light attenuation can be measured using a two part instrument comprised of a light source and a photo-detecting transducer. The photo-detecting transducer is designed such that it responds when subjected to the intensity of the light source. The transducer produces an output that is linear with the amount of light it receives. When a light source and transducer are arranged across a fixed path length, quantitative information can be inferred from the measured output.

METER APPLICATION

The operating principle for all optical density meters is generally the same, however the instrumentation used and the calculations performed depend on the application. The FRL uses ODMs for two primary applications: custom experiments and fixed location.

Custom Experiments

In custom experiments the instrument placement is scenario dependent. Often times ODMs are used in experiments involving a compartment or structure; the ODM can be placed in an area removed from the fire that is not expected to have high temperature exposure. This application provides a local smoke measurement where multiple ODMs can be used in a single experiment [1].

Fixed Location

Fixed location refers to applications where the ODM is mounted to a duct and measurements are performed on the sample passing through the duct. The FRL Fire Product Collectors and Cone Calorimeter are equipped with ODMs mounted to the duct several diameters downstream of the collection hood [2]. This application provides an integrated measurement of the smoke produced by the experiment.

THEORY

Light absorption by gas molecules is characterized by an absorption coefficient; light scattering by particulates is characterized by a scattering coefficient. These combine to produce a spectral extinction coefficient, k_λ, that represents the total attenuation of light by a given medium. The extinction coefficient can be viewed as a proportionality coefficient in the expression that relates the differential change in light intensity as it passes through a differential medium [3]:

$$dI_\lambda = -k_\lambda I_\lambda dL \qquad (1.1)$$

In this expression, I_λ is the spectral light intensity and L is the path length that the light passes through a medium. Equation 1.1 can be rearranged and integrated to produce:

$$\ln\frac{I_{\lambda,L}}{I_{\lambda,0}} = -\int_0^L k_\lambda dL \qquad (1.2)$$

In a uniform medium, in which k_λ does not vary along the path, Equation 1.2 simplifies to:

$$k_\lambda = \frac{1}{L} \ln \frac{I_{\lambda,0}}{I_{\lambda,L}} \quad (1.3)$$

In this expression $I_{\lambda,0}$ is the intensity of the light at its source, and $I_{\lambda,L}$ is the intensity of the light reaching a detector at the end of the path. Equation 1.3 applies strictly to monochromatic (laser) light, however it is often generalized for use with broadband light sources, such as white light, by removing the spectral dependence (λ). Additionally, a correction factor, f, is sometimes applied to account for nonlinearities in the measurement system:

$$k = f \frac{1}{L} \ln \frac{I_0}{I_L} \quad (1.4)$$

The correction factor f is calculated from the measured intensity I_L through a filter with known optical density [4]. The optical density per meter, *D*, (sometimes referred to as simply the optical density) is calculated as follows [5]:

$$D = f \frac{1}{L} \log_{10} \frac{I_0}{I_L} \quad (1.5)$$

The optical density per meter is related to the extinction coefficient according to D = k/2.3.

FireTOSS Calculations

FIRE PRODUCT COLLECTOR

The relation generalized in Equation 1.4 is used to calculate the extinction coefficient for both laser and white light measurements. The rate of smoke release (RSR) is then calculated as the product of the extinction coefficient and the product volumetric flow rate in the duct:

$$RSR = k\dot{V} \quad (1.6)$$

A third quantity that is of interest is the total smoke released (TSR). This is obtained by integrating the RSR rate over time [4].

CUSTOM EXPERIMENTS

Percent obscuration, O, is used in visibility calculations and is calculated as follows [6]:

$$O = 100\% \left[1 - \frac{I_L}{I_0} \right] \quad (1.7)$$

Percent obscuration per unit length is used in detector design and is compared against manufactures' specifications for the detectors. Percent obscuration per meter is calculated according to [6]:

$$O_{u,meters} = 100\% \left[1 - \left(\frac{I}{I_0} \right)^{1/L_{meters}} \right] \quad (1.8)$$

Uncertainty and Accuracy

The uncertainty of the ODMs was estimated using the guidelines of the National Institute of Standards and Technology (NIST) Special Publication 1007 [7], NIST Technical Note 1297 [8], and the NIST Uncertainty Workshop [9]. The combined standard uncertainty of a ODM is a combination of the uncertainty of its components given by the following equation:

$$u_c = \sqrt{\sum s_i^2 u(x_i)^2} \quad (29)$$

where:

u_c = Combined standard uncertainty
$u(x_i)$ = Standard uncertainty of each component
s_i = Sensitivity coefficient $(\partial/\partial x_i)$

The FRL utilizes ODMs which have different light sources and photo detecting transducers. The uncertainty of each ODM varies depending on the instruments used and the path length measurement. Uncertainty calculations discussed in the appropriate Technical Reference.

Operating Instructions

REQUIREMENTS

1. The assigned operator shall be qualified in accordance with laboratory proficiency requirements.
2. The data acquisition instrumentation shall be calibrated and be marked with the calibration status in accordance with FRL calibration procedures.
3. Optical density meters shall be functionally verified in accordance with FRL procedures.

TEST PROCEDURE

1. Setup
   1.1. All ODM instruments shall be connected to the data acquisition hardware utilizing the smallest input range that will bound the output range of the instrument.

2. Prior to the First Test in a Series
   2.1. Operation of the ODM shall be verified using the appropriate functional verification procedure.

3. Prior to Each Test
   3.1. The output of the ODM shall be verified to be stable.

4. During the Test
   4.1. The output of the ODM shall be recorded for the duration of the experiment.
   4.2. Exception – When the ODM must be taken out of service prior to the end of an experiment due to experiment design or impending damage, the elapsed time at which the instrument was removed and the reason for instrument removal shall be recorded.

5. Post Test
   5.1. If an instrument was taken out of service during an experiment, the out of service time and reason shall be recorded. Calculations shall be repeated with the updated out of service time.
   5.2. If conditions occurred during or following the experiment that could potentially affect the performance of an ODM, a functional verification of that instrument shall be performed prior to its use in future experiments.

Optical Density Meter Documentation Requirements

Optical density meter usage during experiments shall be documented using the FireTOSS experiment design program. The information that the user can document about the optical density meter is shown in Table 1 and Table 2, depending on the type of ODM used. The first column shows the description of input parameter that will appear in the column heading of the FireTOSS experiment design program. The second column shows whether the parameter is required in all cases, and column three describes the method by which the field for each parameter is filled.

Table 1. Data Acquisition Input Parameters for Custom Experiment White Light ODM

Parameter	Required	Input Method
Description	TRUE	User Input
Bar Code	TRUE	User Input
X	FALSE	User Input
Y	FALSE	User Input
Z	FALSE	User Input
Light Source Type	FALSE	User Input from List
Extinction Beam Path Length	TRUE	User Input
C Factor	TRUE	User Input
Smoke Main Detector Zero	FALSE	User Input
Time Out of Service	FALSE	User Input
Out of Service Reason	FALSE	User Input
Chart Number	FALSE	User Input
Procedure for Out of Range Values Max	FALSE	User Input from List
Procedure for Out of Range Values Min	FALSE	User Input from List
Maximum Allowable measurement	FALSE	User Input
Minimum Allowable Measurement	FALSE	User Input

Table 2. Data Acquisition Input Parameters for Fire Product Collector ODM

Parameter	Required	Input Method
Smoke - Main detector Span	FALSE	User Input
Smoke- Main Detector Zero	FALSE	User Input
Smoke - Comp Detector Span	FALSE	User Input
Smoke- Comp Detector Zero	FALSE	User Input
Smoke- White Detector Zero	FALSE	User Input
Smoke- White Detector Span	FALSE	User Input
Smoke- Laser OD Filter	FALSE	User Input
Smoke- White OD Filter	FALSE	User Input
Smoke- Main Laser Detector Filter Signal	FALSE	User Input
Smoke- White Detector Filter Signal	FALSE	User Input
Smoke- Laser Pathlength	FALSE	Automatically Updated
Smoke- White Pathlength	FALSE	Automatically Updated
Smoke- Delay Time	FALSE	Automatically Updated
Smoke – Laser time out of service	FALSE	User Input
Smoke – Laser out of service reason	FALSE	User Input
Smoke – White light time out of service	FALSE	User Input
Smoke – White light out of service reason	FALSE	User Input

References

1. ATF FRL Technical Reference, Optical Density Meter Custom Experiments, ATF-LS-FRL-TR014b.

2. ATF FRL Technical Reference, Optical Density Meter Fire Products Collector, ATF-LS-FRL-TR014a.

3. Incropera, F. P., and DeWitt, D. P., *Fundamentals of Heat and Mass Transfer*, *3rd Ed*., Wiley and Sons, New York, 1990.

4. User's Guide for the Laser Smoke Measurement Unit – For Use with Large Scale Heat Release Systems, Fire Testing Technology, Issue 2.1, 2001.

5. Mulholland, G. W., "Smoke Production and Properties," *SFPE Handbook of Fire Protection Engineering*, 3rd Ed., National Fire Protection Association, Quincy, Massachessetts, p 2-263, 2002.

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8. Taylor, B. N., & Kuyatt, C. E., “NIST Technical Note 1297: Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results,” National Institute of Standards and Technology, Gaithersburg, MD, 1993.
9. Guthrie, W. & Liu, H., “Hands-on Workshop on Estimating and Reporting Measurement Uncertainty,” National Institute of Standards and Technology, Presentation given to CPSC, 2007.