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Kellie Ann Beall, Editor

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Gaithersburg, Maryland 20899

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Design and Testing of a New Smoke Concentration Meter

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An important parameter in assessing the fire safety of a new product is the smokiness of the material with regard to its effect on visibility. Materials with tendency to produce high levels of smoke make it more difficult for people to egress from the affected area. Minimizing smoke is especially important in transportation systems such as planes, trains, and subways. It is also important to avoid smoke deposition in high impact areas like communication systems and computer facilities. Smoke deposition is also a major concern in high cost production facilities where a clean environment is crucial such as for semiconductor fabrication and for pharmaceutical preparation.

One measure of the smokiness of a material is its smoke yield ε, which is defined as the mass of smoke produced/mass of material burned. This quantity varies from 0.005 for flaming combustion of wood cribs to as high as 0.15 for polystyrene. The rate of smoke production during a fire depends on both the value of ε and on the mass loss rate of the fuel. So it is possible for a material with a larger ε to produce less total smoke than a material with a higher burning rate.

The Cone Calorimeter and the NIST Furniture Calorimeter have been used to measure the specific-extinction area of a material σ_f, which is the light extinction coefficient normalized by the mass loss rate of the sample per volume flux through the collection hood. While this is a useful tool for relative comparison of materials, for modeling applications it is more convenient to use the mass concentration of smoke rather than an optical property.

Last year at this meeting we reported that the specific extinction coefficient of flame generated smoke, σ_s, has a value of 8.5 m^2/g with an "uncertainty" band of 2 m^2/g to include the effects of material chemistry and fire scale. With the knowledge of this constant, the mass concentration, m_s, can be determined from the transmission of light through the smoke in the duct via the following formula:

$$m_s = \frac{ln(I_0 / I)}{\sigma_s L} \qquad (1)$$

where L is the pathlength through the smoke and I_0 and I refer to the incident and transmitted light intensity for a monochromatic light source. The universality of σ_s is the impetus for the development of this new instrument.

The advantage of determining the mass concentration by an optical method is that it is much less labor intensive compared to filter collection and allows routine measurement at the same time one is performing a test to measure the heat release-rate.

In order to test practicality of this concept, we have developed a light-extinction system and incorporated in a Furniture Calorimeter at NIST. As with previous light-extinction meters used at NIST with the Cone Calorimeter and the Furniture Calorimeter, this system uses a He-Ne laser and a Si photodiode detector. One major design change was to use wherever possible commercially available components including the light source, detector assembly/optics, and mounting /positioning apparatus. The intention was to provide a design that could become a standard. A number of other changes were made to enable measurements at lower smoke concentrations and to reduce the overall measurement uncertainty:

- A stabilized light source to minimize the intensity drift.
- Measurement of pathlength in the presence of purge air quantified using a glass purge tube.

- A focusing lens and diffuser to minimize the effect of light-beam movement at high temperature.
- Commercial position equipment to simplify instrument alignment.

The initial system included a newly developed diode laser which included a high precision temperature controller to maintain constant laser intensity. This diode laser performed well for small fires, but as the ambient temperature in the building increased for the large fires, the temperature controller was not able to maintain a constant temperature and there was a drift in the laser intensity. The diode laser was replaced with a He-Ne laser together with a laser stabilizer to provide a constant output intensity with a drift of less than 0.1 % in intensity over a ten minute test.

The one component that was fabricated in house was the support assembly for the smoke concentration meter. This consisted of an approximately 1 meter-long section of 15 cm-wide U-channel attached to the 0.5 m-diameter duct with gussets. Both the light source assembly and detector assembly were attached to the U-channel assembly to minimize the effect of the thermal expansion of the duct. The effect of beam displacement was assessed by using "smokeless" natural-gas flames with heat release rates in the range 100 kW to 500 kW. Even for the 500 kW fire operated for 600 s, which is the maximum limit for the furniture calorimeter at NIST, the effect on the transmitted light intensity was minimal.

In addition to the mass concentration, the mass flux of smoke and the yield of smoke can be determined given the stack-flow rate and the mass-loss rate of the fuel. The temperature, velocity, and smoke-concentration profiles were measured to determine the relationship between the line-of-sight average smoke concentration and the cross-section averaged quantity needed for determining the total mass flux of smoke in the duct.

To assess the performance of the smoke meter, four repeat series of experiments with propane fuel at 50 kW, 100 kW, and 450 kW were carried out. A series of pool fire experiments were carried out to provide a more realistic test of the system. Heptane, toluene, and a mixture of heptane and toluene were burned in a 50 cm diameter pan. The mass-loss-rate of the fuel was measured with a load cell allowing the determination of the smoke yield. The heptane tests were performed to enable comparison with literature values of smoke yield and the light-extinction coefficient for the same size pan and same fuel. Toluene has one of the highest smoke yields of any material and was selected to provide test data at the upper limit of intended use.

We believe our design can be followed by other users for incorporation in their systems. In our case, the smoke concentration meter was mounted on an 0.6 m-long section of duct, which was then attached to the existing exhaust duct. The total cost of the components was approximately $8,000, and another $2,000 was necessary for shops to fabricate the support structure and optical ports.