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Multi-point opacity measurement in a fire environment using a network of optical fibres

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ABSTRACT

Opacity measurements were carried out in a smoke layer using a light source and photodiodes located outside the hot environment, using a network of optical fibers to transport the incident and attenuated light. The whole system was designed with protections for the emission and reception points against smoke, droplets and water vapor generated by a water mist system. It was tested first in laboratory conditions in order to assess its stability at high temperature or in a water spray. Its accuracy regarding the transmission measurement was then evaluated using a reference material. It was used after these qualifications steps in a fire smoke layer flowing along a corridor ceiling, in order to provide a stratification profile based on transmittance data. Results were compared to the stratification data obtained with classical thermocouple measurements. The analysis showed similar conclusions without spray: the vertical evolution in temperature and transmission indicated a similar smoke-free layer, around 1.20 m high in the 2.40 m high corridor when smoke was produced by a 250 kW heptane pool fire in a neighboring room. When studying smoke/mist interactions using a nozzle injecting water in the corridor, a perfect mixing was deduced from temperature measurements, while some discrepancies still appeared with the opacimeters, indicating some variations in the particle concentrations. The opacity could serve to predict these concentration profiles and the visibility in the smoke/droplet medium.

1. Introduction

When a fire is burning in an enclosure, for a wide range of compartment fires, there is an obvious difference between an upper layer filled with smoke and a lower layer constituted of fresh air. The smoke layer is hot and attenuates light and radiation, whereas the smoke-free layer is cold, heavier and quite transparent. These stratification phenomena are widely investigated for fire propagation and safety studies. In this frame, temperature measurements using thermocouple trees are often involved in experimental campaigns [1]. Such measurements are easy, cheap and can be obtained in confidence. The estimation of the measurement uncertainty in parallel is also easy with this instrumentation. The data analysis quickly leads to the smoke layer thickness and its evolution. Indeed, the temperature vertical variation is generally contrasted between the hot smoke and the fresh air in the free-smoke area. Correlations exist to estimate a smoke-free layer height based on this variation. We can cite the so-called *N%* rule by Cooper et al. [2], the model by Quintiere [3] and Janssens and Tran [4] considering temperature integrals and the models by He et al. [5]. Even if these relationships were initially developed to predict mass flows through openings or to compare experiments with two-zone model predictions, they are still used nowadays, in particular to render an idealized representation of the fire where two layers are observed. For instance, the well known CFD code Fire Dynamics Simulator (FDS) uses the model by Janssens and Tran [4]. Beside the thermal effects associated to the smoke, its opacity is of interest in fire safety. Smoke includes soot particles in suspension which induce absorption and scattering phenomena and attenuate the visible light. Smoke opacity affects the visibility for any people supposed to escape from the fire area. Thus, smoke opacity is an interesting quantity to qualify people escape conditions. It can be linked to the visibility or to characteristic extinction coefficients through simple relationships, as found in [6] for example, from the pioneering works by Jin and Yamada [7], Rasbach and Phillips [8] or Babrauskas [9] among others. In particular the well-known relationship by Jin links the visibility to the inverse of the extinction coefficient of the smoke. Similarly, the relationships between the extinction coefficient and the opacity can be used to characterize the smoke density in some standardized tests [10,11].

In fire tests, smoke opacity is hardly measured whereas it

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provides another way to study smoke production and track its flow. Opacity is frequently deduced by measuring the amount of light transmitted along an optical path with Beer–Lambert's law. For instance, we can cite the references [12,13] in which a wide spectrum band emitter was used to study fire at the compartment scale. We can also cite Barakat et al. [14] who used monochromatic beams in the visible range to study smoke produced by different fire loads and to assess its extinction properties as a function of wavelength. The approximation based on the Beer–Lambert's law omits multiple scattering phenomena. It can be correct if we assume that smoke carries soot particles with moderate size and concentration. The exponential form of this law leads to express the smoke characteristics in terms of the optical density equal to the natural logarithm of the transmittance through the smoke layer. The particles in smoke are consequently investigated with this measurement method combined with models for the attenuation properties. The scattering may start to be more important when considering droplets in suspension. Then, the basic relationships based on the Beer–Lambert's law may become inaccurate, unless a collimated beam is considered, with detection in a very narrow angle and considering an extinction coefficient for the attenuation property (which involves both absorption and scattering). In this case, the opacity is expected to provide an information on the visibility, affected by both the smoke and the droplets simultaneously.

Our research is partly dedicated to study the interaction phenomena between water spray and smoke flow. The objective is to assess the impact of water sprays on the smoke observing modifications in the temperature and the opacity in the visible spectrum range. The practical objective is to assess the impact of water sprays on people evacuation conditions. We also compare different technologies, among them conventional sprinkler systems generating large droplets with high water flow rate under low operating pressure and more recent water mist systems which are spreading water into a cloud of very small droplets. Such a research requires real scale tests and our study is based on a fine description of the thermal and optical environment (see Ref. [15]). The idea is to install trees of usual thermocouples and also trees of opacimeters to get simultaneous vertical evolutions. However, the induced environment in the fire tests is particularly harsh since opacimeters are placed in hot gases transporting soot and water vapor. Moreover, when the spray is activated, there is a large amount of water droplets both in suspension or directly sprayed in the opacimeter direction. Thus, in addition to thermal effects, opacimeters are subjected to soot deposition, water vapor condensation and also water droplet deposition. Usual opacimeters are not designed for operating in such conditions. In particular, photodiodes and even more laser diodes are very sensitive to temperature and do not operate at high temperature. In this context, a new opacimetry system was developed for the present study, which is able to operate in the fire environment, even if a spray system is activated. The present paper describes the design of the opacimeters, the evaluation of their performances at laboratory scale and their application to real scale fire tests where smoke/spray interactions are studied. In that frame, the real scale experimental setup is described and the experimental results are presented. Moreover, the smoke stratification is discussed based on temperature and opacity. In other words, the data provided by both measurement methods are compared.

2. Principle of the opacimeters involving the optical fiber network

In a previous work [15], the transmittance measurement was based on the attenuation of a laser beam at wavelength 635 nm. The device involved a laser diode used for the beam generation and a photo-diode used as a detector located at 10 cm from the diode on the line of sight. The photodiode converted the amount of transmitted light in voltage signal. Laser diodes and detectors were each protected by a small box with a hole for the laser beam path in order to avoid any droplet deposit on the optical surfaces. All the laser diodes and photodiodes were supplied with batteries located inside the protection boxes. This installation was practical and cheap. However, several problems were encountered, which did not allow a smoke characterization in confidence during fire. First, laboratory tests showed that both the selected photo-diode and laser diode cannot be used with full confidence above 50 °C, especially because the laser diode is very sensitive to temperature and even becomes faulty if the temperature is too high. That is why laser diodes are often used with a thermoelectric cooler in order to get a stable emission. Secondly, a deposit of soot and droplets was also suspected. We concluded that a false attenuation may be measured if all these problems are not solved.

This conclusion guided us toward a system involving a source and a receptor protected from the harsh environment. First of all, it was decided to use a light source located outside the high temperature area, using optical fibers to guide the incident light toward the measurement area. Similarly the light collected after the crossing through the medium (smoke and/or droplets) is transported outside the harsh environment via optical fibers up to a photodiode. Some collimators are used both in order to obtain a collimated laser beam at the exit of the fiber that brings the light inside the medium and to focus the beam inside the fiber which carries the collected light to the photodiode. The collimators lenses have to be protected from the deposit of soot and water droplets and from water vapor condensation (the air is very wet due to water vapor contained in smoke and due to the evaporation of the spray). In order to avoid this, the collimators are put at the end of small tubes (70 mm long) which are encapsulated in a pressurized protection box.

In other words, the opacity measurement involves a light source and a detector as usual, but the basic idea in the present work is to use an optical fiber network in order to avoid the perturbation of the light source by the hot environment loaded with small particles and humidity generated by the smoke–spray mixing. This is illustrated in Fig. 1 with a schematic view on the left and a picture of the setup on the right. A fiber-coupled laser source (Thorlabs MCLS1) at 642 nm is used. The temperature of the laser diode is controlled with a Peltier device in order to warrant the signal stability. The drift of the optical power of the source is less than 0.02% during the experiment duration (1000 s). The signal is split by using 1×4 single mode couplers in cascade in order to provide 16 different signals in parallel. Each signal is guided with an optical fiber especially chosen for a possible use at high temperature toward the emission box, with a lens allowing the collimation of the incident light. A variable path line through the smoke/droplet mixing is possible between 10 cm and 30 cm. The emission and the reception boxes are set on the same metallic support: a bar with a section of 2 cm × 2 cm to allow a correct and stable alignment. As explained before, an air blowing device is used in order to prevent from droplets, soot and water vapor in excess flowing inside the box. The measurement itself is a voltage signal delivered by the photodiodes between 0 and 10 V. The reference signal is measured before the fire ignition and after the experiment to check the good stability of the device. The ratio between the voltage registered during the experiment and the reference signal yields a transmittance as a function of time.

3. Opacimeter qualification at laboratory scale

This device was first qualified through laboratory tests in two