Photoacoustic Smoke Detector

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Cross sensitivity to non-dangerous species is probably the major problem of modern smoke detectors. It is both the source of nuisance false-alarms and the factor that limits the sensitivity to real fire situations. In this paper, we describe the use of a photoacoustic aerosol sensor as an alternative smoke detector. Photoacoustics using visual light sources is mainly sensitive to the amount of black carbon in air and has a low or zero cross sensitivity to the usual sources of false alarms. Our sensor differs from most resonant photoacoustic sensors in that its resonant chamber is open in order to allow the smoke to enter it by pure diffusion. It is equipped with a resonance tracking system that monitors the changes in the resonance frequency caused by environmental conditions or an actual fire situation. Our tests show that our photoacoustic sensor has a good sensitivity to the different standard test fires and performs specially well in the case of open fires, which are hard to detect with the available commercial sensors. This makes it an ideal candidate to fill in an existing gap in the fire detection devices.

1 Introduction

Fire prevention and detection is one of the most important tasks of modern building automation systems. The monitoring of smoke is still the most popular way of detecting fires. Unfortunately, the so called smoke detectors have their down side. Their incidence of false alarms is high and can hardly be reduced, since smoke detectors have a cross-sensitivity inherent of their detection method. The list of materials that cause false alarms is long and even dew droplets can trigger them. Furthermore, the sensitivity of a smoke detector is established based on the cross-sensitivity through a standard test that uses paraffin droplets. An unrealistic measurement since paraffin has no clear relation to fires (we shall comment on other standard tests, performed with real smoke, later on in this article).

In this paper, we present a prototype of a smoke detector based on photoacoustics (PA). A photoacoustic detector overcomes the problem of false alarms by selectively detecting the amount of black carbon in air. Black carbon is a very efficient light-absorber in almost the complete electromagnetic spectrum. The visual range is particularly interesting since most of the atmospheric gases have only very week absorption lines there. Previous work shows that the detection of black carbon in this range using photoacoustic spectroscopy can deliver good results (see, e.g. [1, 2]). Black carbon is one of the main components of soot. It is produced in most combustion processes and is therefore a signature of fires.

The sensor was specifically designed for the fire detection industry. Our idea was to develop a reliable sensor that can be used by everyone, starting from the general public that has a limited budged for this kind of devices up to industrial buildings where complex systems are required.

2 Experimental

In this section, we will give a short description of our smoke detector and the evaluation procedure that we used. For more detailed data please refer to [3].

2.1 Photoacoustic resonant cell

Contrasting with the majority of the existing photoacoustic cells, ours has a very simple geometry. It consists of a metallic cylinder (diameter 16 mm and length 30 mm) completely open on both sides. This was necessary because, as in other smoke detectors, the smoke has to enter the sensor chamber by pure diffusion, which means that we do not use any gas flow system. The photoacoustic cell has no windows, acoustic filters or any other noise rejection system other than the signal processing electronics.

Figure 1 shows a schematic view of the resonance cell. The first azimuthal resonance mode is used for detection (approximately 13.5 kHz at normal conditions). The light source is a 650 nm (5 mW optical output power) laser diode. The relevant cell parameters are the quality factor $Q = 30$ and the cell constant $R = 2.2$ Pa m/W, as measured in photoacoustic operation using a graphite sparc aerosol generator (Palas GFG 1000).

The speaker shown in fig. 1 is used to measure the changes of the resonance frequency. These changes are not so critical for most photoacoustic applications. They are induced by changes in the atmospherical conditions, which happen slowly, and can therefore be compensated after several measurement cycles (for instance, once every hour). The shift of the resonance frequency becomes critical only for very precise measurements or for applications where, as in the case of fires, the pressure and

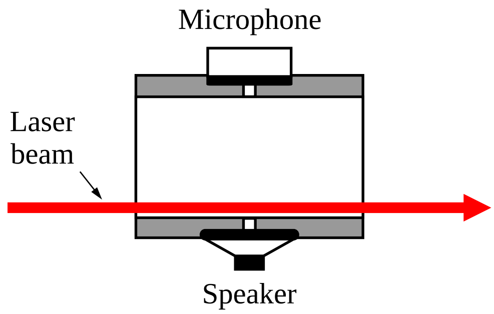

Figure 1: Schematic view of the PA cell

temperature vary very rapidly.

We monitor the changes in the frequency of the first azimuthal resonance by acoustically tracking the second azimuthal mode. This can be done because the ratio of the two frequencies remains constant. A similar technique, for mid- to high-Q resonators, has already been used in photoacoustics [4]. In our case, we track the phase and not the intensity of the signal by means of a Phase Locked Loop (PLL). The advantage of this method is that it can also be used for low-Q resonators. Figure 2 shows a schematic view of the resonance tracking electronics. In our setup, the PLL must trace the second azimuthal resonance (~ 21.4 kHz). Its original phase is 0° but the phase is then shifted by the band pass filter of the preamplifier. The PLL-controller must compensate the shift and generate the signal that drives the speaker. The computer reads the output frequency and calculates the frequency of the first azimuthal resonance.

2.2 Test fires

The natural way of testing a smoke detector is by measuring its response to the smoke produced by the combustion of different materials. The relevant tests are summarized in the European Standard Norm EN-54 for fire detectors and fire alarm systems [5]. The tests include the open combustion of wood (test fire 1 or TF1), polyurethane (TF4), and a n-heptane and toluene mixture (TF5) and the smoldering combustion of wood (TF2) and cotton (TF3). As one can imagine, different fuels produce smoke of different characteristics. Nevertheless, it is the type of combustion, i.e. smoldering or flaming, what determines the optical properties of smoke [6, 7]. The norm also establishes several other parameters like the minimum dimension of the test room (9 m $\times$ 6 m $\times$ 3.8 m, $L \times W \times H$) and the position of the sensors inside the chamber.

We used a reduced measurement box to produce the test fires (only 1 m $\times$ 1 m $\times$ 1 m). The tests procedures were similar to the description of the EN-54 standard but the amount of combustible material was adapted for the chamber size. We measured the optical properties of the smoke produced in our test box to ensure that our tests

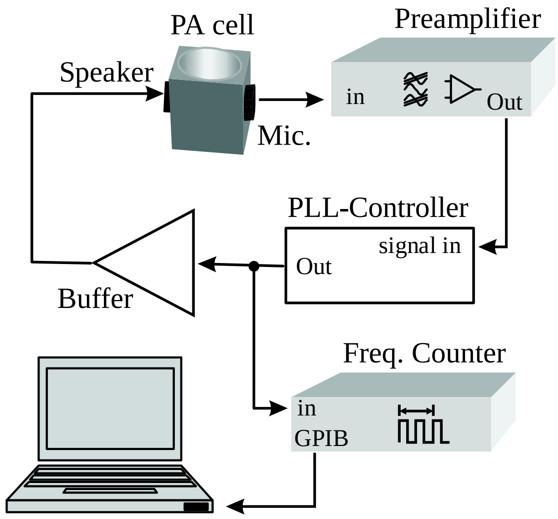

Figure 2: Resonance tracking circuit. The phase of the second azimuthal resonance is continuously monitored by a Phase Locked Loop (PLL). Theoretically, the PLL should locks to the frequency whose phase is equal to zero (i.e. the second azimuthal frequency). The electronics must compensate for the phase shift induced by other factors like the band pass filter of the preamplifier.

were as close as possible to the norm tests. This was done using the diesel particle scatterometer [8]. Our measurements show that the smoke of the reduced box is equivalent to the smoke of the norm chamber. We also added a small ventilator inside the test box to ensure a uniform mixture of air and smoke during the tests.

The PA sensor was mounted inside the cell with the cylinder axis parallel to the top of the box, 5 cm bellow it. Two other commercial sensors were mounted for reference: a photoelectric (i.e. light scattering) sensor and a light extinction sensor. The photoelectric sensor also provided a measurement of the temperature inside the box. The extinction sensor (known as MIREX) is the reference sensor for the EN54 test fires. The signal of the smoke detectors is therefore usually given in light extinction equivalent units. The MIREX has an optical path of a little more than one meter (measured across the test box) whereas the two other sensors have an optical path of only a few cm.

3 Results and discussion

3.1 Calibration

There is no standard defined in the fire detection industry for the amount of black carbon in air. The measurements of smoke, including the non-optical sensors, are always referred to the "extinction equivalent" of the sensor given in either %/m or dB/m. This is, the sensors are calibrated in a procedure that uses paraffin droplets to simulate smoke. The reference light extinction is measured by means of a MIREX sensor. The alarm levels of the calibrated sensors are then set to a specific extinction value. This creates several problems when the detectors are exposed to real smoke. For instance, for smoke detectors based on non-optical principles, like the ionization detectors, there is no clear relation between this test and the performance of the detectors in a real fire. Furthermore, paraffin cannot be use as a reference substance for our photoacoustic detector since its refractive index is real in the visual range making it nonabsorbent.

The natural way of calibrating a photoacoustic sensor is using a standard black carbon aerosol generator. Nevertheless, in order to compare its performance with other smoke detectors, we have to use the standard light extinction units. We calibrated our sensor by comparing its signal to the signal of the MIREX during a test fires that produce black smoke. In these tests, the extinction is dominated by the absorption of light and the signal of the photoacoustic detector should equal the signal of the MIREX. The small difference between the signal of the two sensors should be equivalent to the signal of the scattering sensor (i.e. scattering plus absorption equals extinction). Some difference may still arise since all three sensors use different wavelengths and both absorption and scattering are wavelength dependent. Still, our results suggest that this is a valid approximation within the scope of our tests.

3.2 Comparison with other smoke detectors

Figure 3 shows some representative measurements of the evolution in time of the two different combustion types. The TF5 is a flaming fire that produces black smoke and the TF2 is a smoldering fire that produces white smoke. The light extinction is dominated by absorption in the case of the black carbon rich smoke produced by the flaming fire. Scattering is the dominating process in the case of the smoldering combustion. Other test fires gave similar results. It is no surprise that the extinction sensor performed well on both tests since its signal serves as measure for the other sensors.

In general, the signal of the scattering and the photoacoustic sensor complemented one another. The photoacoustic sensor had a very fast reaction in all flaming fires, which are difficult to detect with the available commercial detectors (see [3]), and only a moderated signal in the case of the smoldering fires. Nevertheless, even in the latter case, the photoacoustic signal was always present and clearly separated from noise. This is, our detector can measure the moderated concentration of black carbon in white smoke. The limit of detection of the photoacoustic

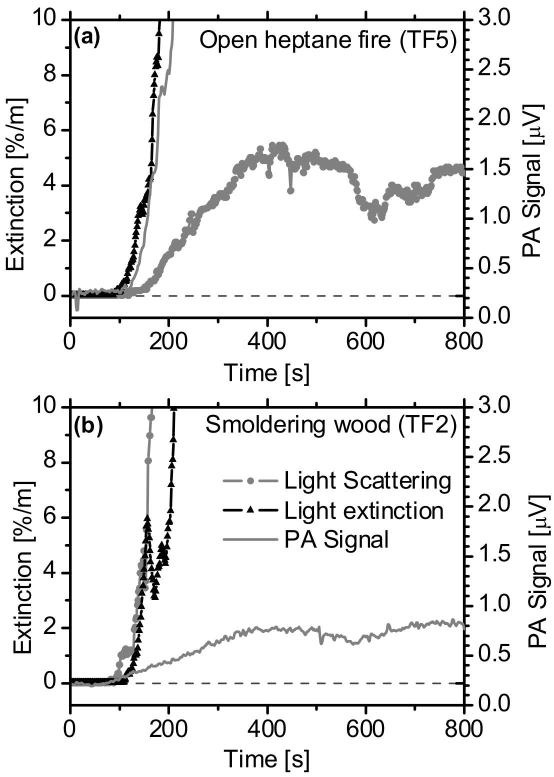

Figure 3: Evolution in time of the scattering, extinction, and absorption (photoacoustic detector) of light during two different test fires. The raw signal in μV of the PA sensor is shown at the right of the graph. The calibrated signals, including the photoacoustic sensor, are shown to the left of the graph. The left axis is defined in terms of the light extinction sensor. Therefore, the light scattering and photoacoustic signal can at most equal that of the extinction sensor.

sensor is 0.08 μV, according to the standard deviation of the background signal and the 3σ criteria. This is equivalent to a light extinction value of approximately 0.3%/m and well bellow the signal of smoldering fires.

It is worth to mention that both the scattering and the extinction sensor have the problem of cross sensitivities. They cannot distinguish if the signal comes from a real fire or a non-dangerous situation. In contrast, the signal of the photoacoustic sensor is only present in the case of materials that contain black carbon. It can be used to discriminate between a real fire and a potential false alarm.

It is still not clear if photoacoustics by itself can be use as an universal fire detector. However, it has been shown that the combination of different detectors can result in a reduction of false alarms [9]. A combination of photoacoustics with another technique, e.g. one with a better sensitivity to smoldering fires, would result in a very fast detection of fires and a good discrimination of other species.

3.3 Final remarks

Further tests are needed to decide if the PA sensor alone can be used as a smoke detector system. A first step will be to repeat the series of test fires in the actual chamber described by the norm.

The final smoke detector must also be competent in the economic aspect. Therefore, the choice of light source and other components was primarily motivated by price restrictions. In the particular case of the light source, the 650 nm laser diodes are used as standard light sources for DVD players and are available at good prices. Several wavelengths may also come in question in a near future. For instance, our tests suggest that 532 nm is also a viable wavelength. The issue of cross sensitivity to NO_2 may not be a problem since this particular molecule is also produced during fires.

It would also make sense to introduce a standard for fire detection based on the amount of black carbon in air. The current definition in terms of extinction is bounded to the high incidence of false alarms. Even non dangerous combustion byproducts like cigarette smoke would be better characterized in terms of black carbon. For instance, cigarette smoke is an efficient scatterer but has only a moderated amount of black carbon. A norm based on black carbon will ensure that only extremely high concentrations of cigarette smoke can trigger an alarm. On the other hand, flaming fires produce large quantities of black carbon and would be detected earlier. This is very convenient because flaming fires develop much faster than smoldering fires and early warnings could make a big difference. Finally, the detection of fires based on the amount of black carbon would drastically reduce the amount of false alarms, since they are mostly caused by materials that do not contain any.

References

[1] D.M. Roessler and F.R. Faxvog. Optoacoustic measurement of optical absorption in acetylene smoke. *J. Opt. Soc. Am.*, 69:1699–1704, 1979.

[2] K.M. Adams. Real time *in situ* measurements of atmospheric optical absorption in the visible via photoacoustic spectroscopy. 1. evaluation of photoacoustic cells. *Appl. Opt.*, 27:4052–4056, 1988.

[3] A. Keller, M. Rüegg, M. Forster, M. Loepfe, R. Pleisch, P. Nebiker, and H. Burtscher. Open photoacoustic sensor as smoke-detector. *Sensors and Actuators B*, 104:1–7, 2005.

[4] G.Z. Angeli, Z. Bozóki, A. Miklós, A. Lörincz, A. Thöny, and M.W. Sigrist. Design and characterization of a windowless resonant photoacoustic chamber equiped with resonance locking circuitry. *Rev. Sci. Instrum.*, 62(3):810–813, 1991.

[5] European committee for standarization. *EN54: Components of automatic fire detection systems*, 1987.

[6] A. Keller, M. Loepfe, P. Nebiker, R. Pleisch, and H. Burtscher. Online determination of the refractive index of test fires. Submited to Fire Safety Journal, 2005.

[7] A. Keller, M. Loepfe, P. Nebiker, R. Pleisch, and H. Burtscher. Online determination of the refractive index of test fires. In Laws P. Luck, H. and I. Willms, editors, *Proceedings of the 13th International Conference on Automatic Fire Detection AUBE'04*, pages 547–560, Duisburg, Germany, September 2004.

[8] A.J. Hunt, M.S. Quinby-Hunt, and I.G. Sheperd. Polarized light scattering for diesel exhaust particulate characterization. In *Proceedings of the DOE Diesel Engine Emissions Reduction Workshop*, Castine, MA, July 6-9 1998.

[9] C.D. Litton. The use of light scattering and ion chamber responses for the detection of fires in diesel contaminated atmospheres. *Fire Safety J.*, 37:409–425, 2002.