TECHNICAL REPORT

Evaluation of high sensitivity flat-panel gaseous detectors of flames, sparks and smoke

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ABSTRACT: The early detection of dangerous events, such as large-scale fires, is critical to prevent the subsequent loss in term of human lives and damage to infrastructure. Here we report about the latest evaluation of the performance of solar blind flat-panel sensors developed by us, for the detection of flames, sparks and smoke. These developments will make it possible to build detectors almost 1000 times more sensitive than the best commercial flame sensor presently available on the market, with 100 times better time resolution, and with ultraviolet imaging capability for flame visualization.

KEYWORDS: Photon detectors for UV, visible and IR photons (gas) (gas-photocathodes, solid-photocathodes); Gaseous detectors; Micropattern gaseous detectors (MSGC, GEM, THGEM, RETHGEM, MHSP, MICROPIC, MICROMEGAS, InGrid, etc)
1 Introduction

In the fight against fire, it is very important to detect flames at the earliest possible stage, in order to effectively implement all necessary actions for its suppression. Various commercial flame detectors are available on the market, which are sensitive either to the electromagnetic radiation emitted by a flame or to the subsequent increase in temperature of the air, or to the smoke produced. Detectors sensitive to radiation are generally more expensive, with respect to thermal or smoke ones. Nevertheless their main advantage is that they can detect the appearance of a fire at relatively large distances. Moreover, these flame detectors can respond faster and more accurately than a heat or smoke detector, due to their intrinsic detection mechanism.

There are several types of such detectors, sensitive either to ultraviolet (UV), or to infrared (IR) radiation, or their combination. UV sensitive flame detectors operate in the spectral range 185–220 nm, where the Sun radiation is fully blocked by the ozone contained in the upper layer of the atmosphere. They can operate since, at the ground level, air at relatively short distances (typically between 100 and 500 m, depending on weather conditions), is transparent in the spectral range cited above, where UV radiation is emitted by flames.

The use of this spectral interval presents great advantages compared to the use of the visible spectrum, due to the possibility of recognizing flames even against a strong sunlight background.
UV sensors are classified by their sensitivity. The highest sensitivity, according to EU standards, is provided by the so-called "Class 1" detectors, which are able to detect a \(30 \times 30 \times 30\) cm\(^3\) flame at a distance of 20 m in 20 s. An example of Class-1 flame sensor is the Net Safety UVS-A [2], shown in figure 1. It is a gaseous detector filled with pure Ar, featuring a metallic cathode. UV photons, emitted by a flame, extract electrons from the cathode by means of photo-electric effect and trigger a glow discharge. The signal amplitude is independent of the number of primary photoelectrons triggering the discharge and, consequently, it cannot distinguish among single photons, bunches of photons arriving at short time intervals, or cosmic rays. The dead time of such a sensor is about 1 ms.

![Figure 1](image)

**Figure 1.** Photograph of Class-1 UV sensor (Net Safety). For comparison, our single-wire detector with a CsI photocathode is also shown on the right [1].

In the past years, much experience has been gained using photosensitive gaseous detectors in high-energy physics experiments (see, for example, [3–5]). With the aim to export this expertise for purposes of environmental monitoring, a new concept for a flame sensor was then proposed: a proportional gaseous detector, operating in avalanche mode with a discharge quencher gas mixture (made of polyatomic and noble gases), combined with special high sensitivity UV photocathodes, either solid, like Caesium Iodide (CsI), or gaseous, like vapors of ethylferrocene (EF) or terakis(dimethylamino)ethylene (TMAE) [6].

In these detectors, UV photons from a flame produce photoelectrons from the solid photocathode, or directly in the gas mixture, which drift to a multiplication structure (wires or holes, depending on the detector type), and trigger an avalanche. The typical signal generated by the avalanche, readout with optimized electronics, has a duration of the order of \(\mu\)s. If the signals produced do not overlap in time, which is typically the case when the counting rate is below \(10^5\) Hz, their signal amplitude distribution follows the Furry’s law at low gas gains and a Polya-type distribution [7] at high gains. On the contrary, sparks occurring in a certain monitored area (like a house, a factory, etc.) are characterized by very short and intense flashes giving rise to a series of pulses practically superimposed to each other, resulting in signals whose amplitude is many times larger, and this gives also the possibility to distinguish flames from sparks. Detectors operated in proportional mode offer also another unique possibility: to detect simultaneously flames and smoke, as described in section 4.
One of the first options tested consisted in a single-wire counter equipped with a CsI photocathode or filled with a photosensitive gas, operated in flushed mode (namely new fresh gas mixture is continuously flushed through its volume). Later on, Thick Gas Electron Multiplier (TGEM) and TGEM with resistive electrodes (RETGEM) both flushed with gas were also tested. Some results of previous studies in this field are found in refs. [6, 8–11]. In particular the sensitivity relative to a Class-1 detector for some prototypes, the temperature interval within each detector can operate with high sensitivity, as well as their ability to detect flames in direct sunlight conditions are reported in table 1. The total relative uncertainty of these measurements is lower than few percent. As can be seen, depending on the specific design, the developed detectors have $10^2$ to $10^3$ times larger sensitivity than the best commercial sensors.

Table 1. Compilation of results from refs. [6, 8–10] and confirmed by us [11]. Here we present the most important parameters, in particular relative sensitivity, whose method of measurement is explained in section 2. The results refer to detectors with a window 30 mm in diameter and that operate in gas-flushed mode. Abbreviations SW stands for Single Wire counter. “Special RETGEM”, able to operate in TMAE vapors, is described in ref. [12].

| Detector type     | Photocathode | Relative sensitivity | Temperature interval (°C) | Solar blindness                  |
|-------------------|--------------|----------------------|---------------------------|----------------------------------|
|                   | SW           | SW                   | SW                        |                                 |
| Photocathode      | CsI          | 1140                 | [-100, +60]               | no (in direct sunlight)         |
|                    | CsI + filter | 230                  | [+10, +60]                | yes                             |
|                    | TMAE         | 1180                 | [+20, +60]                | yes                             |
|                   | EF           | 120                  | [+20, +50]                | yes                             |
|                   | CsI          | 670                  | [+20, +50]                | yes                             |
|                   | EF           | 80                   | [+10, +60]                | yes                             |
| RETGEM            | Special RETGEM |                     |                           |                                 |
|                   | TMAE         | 900                  |                           |                                 |

These results are very encouraging, and urged to continue on this track, and to optimize this kind of detectors for real on-the-field outdoor applications as indicated below.

A very important characteristic that restricts the search for suitable photocathodes to be used outdoor is the fact that they should also be solar blind, namely they should have high efficiency in the spectral region 185 to 250 nm, where flame emission is relevant, and almost zero sensitivity for radiation characterized by a wavelength larger than 260 nm, where the sunlight at the Earth surface is still extremely intense.

A photocathode made of CsI, for instance, is characterized by high efficiency to UV, but is not sufficiently solar-blind, so detectors featuring it would need some kind of filter in order to be able to detect flames under direct sunlight, which implies more complexity and an increased cost of the sensor.

Outdoor operations also require stable operation over a wide temperature interval, typically from -40 to +50°C, so this aspect has to be carefully addressed as well.

Of course, all detectors for commercial applications should be sealed.

The aim of this work was to develop and test, sealed high sensitivity detectors of flames, sparks and smoke, able to operate outdoor in direct sunlight conditions without filters and over a wide temperature interval. To accomplish this goal, we performed tests of several solid solar blind photocathodes, we chose the most appropriate and combined them into special designs of gaseous detectors optimized for our applications: Multi Wire Proportional Chamber (MWPC) and TGEM/RETGEM [13] cascade detector. Since some solar-blind photocathodes may be characterized by a lower sensitivity to UV with respect, for instance, to CsI, we compensated this drawback...
by using large-size photocathodes, typically in the form of flat-panels. Flat-panels are particularly
good to be used here, since they nicely adapt to the geometrical characteristics of the detectors
used, and easily allow coverage of large surfaces.

The article is organized as follows: section 2 describes the tests we carried out of various solar
blind photocathodes. Section 3 presents the studies on some sealed large area detectors. In section 4
a sensor able to detect simultaneously flames and smoke is described. Finally, section 5 contains a
summary and a discussion of the main results.

2 Solar blind photocathodes

There are many options for the choice of photocathodes suitable for our application (see, for example,
ref. [14]). In our case, as mentioned above, photocathodes should have high efficiency at least in the
spectral region 185–220 nm and almost zero sensitivity for radiation characterized by a wavelength
larger than 250 nm. These requirements restrict the search for appropriate photocathodes.

2.1 Tunable double layer CsI photocathodes

Among the photocathodes tested, the most attractive so far was made of CsI, due to its high efficiency
and excellent temperature stability (see table 1). This material, if necessary, can be exposed to air for
5–10 minutes, which simplifies its handling. A flame detector with this photocathode operates well
inside buildings. However, for outdoor applications it requires filters for suppressing the extremely
strong long-wavelength radiation from the Sun and large-area filters are not commercially available
or very expensive to build.

The exploratory studies briefly presented below are aimed to develop a technology that allows
to suppress the CsI photocathode sensitivity at long wavelengths by coating its surface with a thin
film of appropriate material. A photoelectron, escaping the CsI surface, has a kinetic energy $E_k$:

$$ E_k = h\nu - \phi $$ (2.1)

where $\phi$ is the CsI electron affinity and $h\nu$ is the photon energy. If the CsI surface is coated with
a film, it will serve as an additional obstacle to the photoelectrons, before they can enter the gas
contained in the detector (figure 2).

Figure 2. Schematic representation of a CsI photocathode covered with a thin photoelectron filtering layer.

For a given film thickness, the larger is $E_k$, the higher is the probability for the photoelectron to
pass through the film. Therefore, by proper optimization of the film material and thickness, one can
reduce the electrons yield at long wavelengths, while preserving its value at short wavelengths. We named this structure a double-layer photocathode. Preliminary tests of this idea have been carried out in collaboration with the St. Etienne Ecole des Mines [15].

Note that there were already attempts to cover solid photocathodes, for example, SbCs with various thin films (CsI or TMAE) [16–19], but, for a completely different purpose, namely to protect them from the direct contact with the gas, which may cause some quantum efficiency (QE) degradation [20–23]. Although in these tests the effect of suppressing photocathode efficiency at long wavelengths was observed, it was not exploited for light filtering. However, important conclusions can be driven from subsequent studies, performed by several groups [6]. One of them is that the most appropriate materials for the covering layer are alkali-halides and some photosensitive liquids, for example EF, where the transport of free electrons on a reasonably long distance is possible [24].

Some results of our studies, aiming to tune the CsI effective QE, are shown in figure 3 and figure 4. The QE was measured by a standard method, using a spectrograph similar to that described in refs. [25, 26]. As light sources, either a Hg lamp or a H$_2$ one were used. The absolute light beam intensity was determined by a reference PMT calibrated by Hamamatsu. Accuracy of measurements was below $\approx 5\%$ and was mainly determined by the accuracy of the absolute calibration performed by Hamamatsu and also checked by us in some spectral interval. As it can be seen, a Potassium Iodide (KI) layer deposited on the top of a CsI photocathode provides the desired effect. In contrast, even relatively thin metallic (aluminum) filters suppress the photocathode QE both for long and short wavelengths, as shown in figure 3, although in principle it is possible to optimize it exploiting its island-type structure typical at small thickness [27].

![Figure 3](image.png)

**Figure 3.** QE of some photocathodes: bare CsI, CsI covered with a KI layer 10 nm thick and a 20 nm thick aluminum film.

Our preliminary laboratory results indicate that it is possible to produce large area photoelectron filtering layers exploiting this technology and we consider this approach to be the most promising. However, for the moment, this technology is not ready to be implemented for an industrial mass production of flame detectors. Our future task will be to find the best material for this purpose and its optimum thickness.
2.2 Choice of appropriate conventional solar blind photocathodes

We also tested several conventional photocathodes in an attempt to choose those best fitting our requirements. These studies [28] were focused on the search for robust, stable in air, solar blind photocathodes, compatible with gas avalanche detectors. Materials with wide band gap, such as alkali-halides [14] or diamonds (see, for example, [29, 30]) are suitable because they are solar blind. Of special interest are hydrogen terminated chemical vapor deposition diamond films, which have negative electron affinity, making them efficient emitters [31].

Figure 4. QE in arbitrary unit of a CsI photocathode covered with a KI layer at two wavelengths (185 and 254 nm) as a function of the KI layer thickness.

Figure 5. (left) A schema of the test setup photocathode evaluation. The procedure followed is described in the text. (right) Photograph of the detector.

The setup used for photocathode evaluation is shown in figure 5. The photocathode manufacturing was supervised by REMOS. It consists of a single wire counter with an exchangeable disk-shaped cathode, 30 mm in diameter. This has been coated, in sequence, with the following
photo-sensitive layers: CuI, Ni, chemical vapor deposition diamond (CVD), diamond like carbon (DLC), KBr, NaBr (or CsBr) and Sm (which has a low work function, equal to 2.7 eV).

The CuI photocathode was manufactured by treatment of oxide-free Cu with a solution of iodine. For the Ni photocathode we used foils, cleaned of their oxide layer.

Polycrystalline CVD diamond films used for these studies were deposited on a silicon substrate (metalized on the opposite side) heated to 800–900°C using standard methods: either by using a hot filament or by microwave plasma assisted technology in about 50 Torr atmosphere of hydrogen with ≈ 1% concentration of CH₄. Their estimated thickness is 4–5 μm. Some CVD films were additionally treated with H₂ in a microwave plasma. It is known that this increases their QE (see, for instance ref. [31]). However, in contrast to ordinary CVD, which are stable in air, the H₂ treated ones decay in air, so special care is required for their handling.

Amorphous small area (25 mm²) DLC films were first produced by ion beam deposition on a p-type silicon substrate at room temperature with the carbon beam in the energy range 10⁻¹¹⁰³ eV. The samples thickness was around 100 nm. Several large area samples (7 cm²) were manufactured by a magnetron sputtering technique, however their efficiency to flames resulted to be low and therefore the relative results are not reported here.

Alkali-halides were deposited by thermal evaporation techniques and their typical thickness was 0.5 μm.

For each photo-layer, we measured the number of counts, \( N_{pc} \), from a single-wire detector, produced when the photocathode was exposed to the light coming from a commercial candle, placed at a distance typically of 3 m, and then, separately, the number of counts, \( N_{pcS} \), produced by direct sunlight (hitting the photocathodes perpendicular to their surfaces). In all measurements, the same commercial candle model was used, to ensure as much as possible the same emission spectrum and the same intensity of the UV light. After a few minutes from the candle ignition, the intensity of the emitted radiation becomes quite stable. It has been independently monitored with a commercial Class-1 Net Safety UVS-A flame detector and fluctuations smaller than 5% were observed.

At the same time, similar measurements with the candle and the Sun were performed with a commercial Class-1 flame sensor, used as reference, measuring the number of counts \( N_{cl1} \) with the candle and the number of counts \( N_{cl1S} \) with sunlight.

The ratio between the number of counts, recorded in the same time interval, by our detector and the reference one is an estimate of its relative sensitivity with respect to the Class-1 sensor. Namely, \( N_{pc}/N_{cl1} \) is the relative sensitivity measured with the candle, and \( N_{pcS}/N_{cl1S} \) the one measured with the sunlight.

The results obtained are summarized in table 2. The statistical uncertainties of the measurements presented are smaller than 3%. Due to the high efficiency of detectors used it was not a problem to accumulate the necessary numbers of pulses from both detectors during a short period of time. Measurements under direct sunlight were performed during a few selected days when the sky was clear and at the same time, the detector was always placed perpendicular to the Sun’s rays.

The highest sensitivity to flames was achieved with the CuI and Ni photocathodes. These photocathodes have also low \( N_{pcS}/N_{cl1S} \), making them more solar blind with respect to Class-1 detectors and therefore are very promising for outdoor applications. As shown in table 1, they are almost two order of magnitude less efficient than CsI, but they do not require any filter under direct sunlight. Since this kind of photocathode are relatively easy to manufacture, these results open the
Table 2. Relative sensitivities to flame and direct sunlight, with respect to Class-1 detectors, of some tested photocathodes. The different results for the same photocathode correspond to different samples. The largest spread is in the case of CuI heated, we are still learning how to better control this technology that has an impact on the sensitivity.

| Photocathode | CuI | CuI heated | Ni | CVD H₂ treated | CVD microw | CVD hot | DLC | KBr Tremsrn last paper | NaBr | Sm | CsBr |
|--------------|-----|------------|----|----------------|------------|---------|-----|------------------------|------|----|------|
| Relative sensitivity to flame \((N_{pc}/N_{cl1})\) | 9 | 51 | 6 | 4 | 0.6 | 0.2 | 0.2 | 3 | 1 |
| Relative sensitivity to direct sunlight \((N_{pcS}/N_{cl1S})\) | 0.5 | 0.8 | 2 | 4 | 0.8 | 0.1 | 0.2 | 1512 | 385 | 224 | 168 |

possibility to use them in flat-panel designs of gaseous detectors, where the low efficiency per unit area can be compensated by the large surface of the photocathodes.

In our tests, diamonds and alkali-halides photo-layers exhibited lower efficiency, but probably technological improvements might overcome this problem in the future.

The QE of CuI, Ni and some diamond like and alkali-halides photocathode were measured in several works, see, for example [32–37]. However, it is not straightforward to compare these published results with ours, summarized in table 2. The reason is that in the present work, we did not measure directly their QE \(Q(\lambda)\), but its convolution with the flame emission spectrum expressed in number of counts. Nevertheless, the obtained relative sensitivity qualitatively correlates with the known QE of tested materials in the region 190–210 nm [32, 34, 37].

3 Sealed large sensitive area flat-panel detectors

As shown in the previous paragraph, CuI and Ni photocathodes are so far the best candidates for the design of flat-panel flame detectors.

Although they have two orders of magnitude lower QE than CsI (compare the data in table 1 and in table 2), it is possible to increase the sensitivity of the detector increasing its sensitive area. It is worth noting that some commercial Class-1 sensors, for example, the Hamamatsu R2868, due to the feature of glow discharge, have a physical limit on their sensitive surface area of about 1 cm².

In this work, we tested and evaluated two detector kinds, particularly suitable to an increase in the sensitive area: MWPCs and TGEM/RETGEM cascade detectors.

3.1 Sealed GEM-based detectors

One big advantage when compared to other detectors, is the fact that nowadays, GEM-like detectors are commercially available. Additional potential advantages of GEM-based flame detectors are also:

- they can naturally accommodate flat-panels in their design;
- they can have large sensitive areas and are compatible with a large number of gases, including pure noble gases;
• they can be equipped with a segmented readout, and therefore, when coupled with a suitable UV lens system, can provide imaging capability, allowing to determine the position of flames and sparks in space.

There were already attempts to develop sealed gaseous photo-multipliers based on hole-type amplification structures. For example, a sealed GEM-based detector combined with a CsI photocathode has shown excellent stability over time [38]. Moreover, as shown in ref. [39], even more sophisticated photocathodes remain stable in sealed gaseous photomultipliers, if the latter are made of proper materials (such as glass, ceramics, etc.).

In this work, sealed flame detectors, based on thick GEM (TGEM) [40] and Resistive Electrode Thick GEM (RETGEM) [41], are used (see figure 6). These detectors are robust, discharge protected, can be assembled in standard laboratory conditions, and have also low cost in mass production (one euro for 1000 holes, corresponding to $\approx 25 \times 25$ mm$^2$). They consist of a printed circuit boards, often called G-10, a mixture of fibre glass with an epoxy resin, and thus, in contrast to Kapton or glass, it is very porous, leading to large outgassing. In gas-flushed mode, they were already successfully used for detection of Cherenkov photons [13, 42] but it was not proven yet whether they can stably operate in sealed mode.

3.1.1 Setup

The TGEM and RETGEM detectors, operating in cascade mode, are mounted inside a stainless-steel test chamber, having a quartz window and feed throughs to supply High Voltage (HV) and readout the signals (figure 6). The geometrical characteristic of TGEM/RETGEM used are: sensitive area of $10 \times 10$ cm$^2$, thickness $t = 0.4$ mm, hole diameter $d = 0.5$ mm, pitch $s = 0.9$ mm and ring rim $h = 0.1$ mm. The distance between the cathode mesh and the top TGEM electrode was $L_{\text{drift}} = 1$ cm.

![Figure 6](image)

Figure 6. (Left) Schematic representation of a flat-panel detector of flames and sparks, consisting of a TGEM-RETGEM combination. (Right) Photograph of the detector used.

Most of the detector support structures were made of ceramics. In the first test, a simple approach was used for outgassing the system: the chamber and relevant parts of the gas system were heated at $80\div150^\circ$C by means of electric heating tapes wrapped to aluminum foil to ensure heat uniformity. Under these conditions, the chamber was pumped for 7–10 days, reaching vacuum conditions better than $10^{-6}$ Torr.
Later we prepared and started using a dedicated setup, shown in figure 7. It is a metallic cabinet accommodating the detector and the gas system, including bottles filled with photo-sensitive liquids. The temperature inside is regulated with a heating element and maintained automatically at the set value. The temperature uniformity inside the cabined is ensured by two vents.

**Figure 7.** Photograph of the device used for outgassing and filling the sealed gaseous detectors with gas.

After the chamber outgassing, the desired gas was introduced. In most cases, Ne or mixtures of Ne with a small amount of CH$_4$ or CO$_2$ were used at a total pressure of 1 atm, which offers lower operating voltages with respect to other noble gases at the same gas gain. As a UV source, a Hg lamp was used, producing photocurrent due to gas ionization or, in some cases, due to the photoelectric effect from the surface of the detector cathode. For current measurements, a pico-ammeter was used. When the detector operates in a pulse mode, the RETGEM anode was connected to charge sensitive preamplifier mod. ORTEC 142 PC. Signals from it were sent to an amplifiers mod. ORTEC 450, then to a discriminator and finally to a scaler.

### 3.1.2 Test results

The first measurements were done with TGEM/RETGEM in ionization mode at various conditions: with EF vapors at temperature $T = 40^\circ$C, with CuI photocathode in vacuum and CuI photocathode in Ne+20%CO$_2$ at $P = 1$ atm. This allowed for the evaluation of the relative QE, at room temperature, of the CuI photocathode with respect to EF, as shown in figure 8. For this we used a calibration cell made of a similar parallel-plate structure, with a gap $L_{\text{gap}} = 20$ mm in length in which EF vapors can be heated. Through the window the cell is illuminated by the UV light and the photo-current is measured. The QE of EF vapors at the given wavelength and in the case of small absorption of the
UV (detector gap thickness was 1 cm) is, with good approximation:

\[
Q_{\text{EF}} = \frac{Q_{\text{sat}}P_{\text{gas}}L_{\text{drift}}}{P_{\text{sat}}L_{\text{gap}}}
\]

where \(Q_{\text{sat}}\) is the QE at full light absorption, \(P_{\text{gas}}\) and \(P_{\text{sat}}\) are the EF pressure in the detector and the pressure in the calibration cell at which full absorption begins (see below), respectively, \(L_{\text{gap}}\) is the gap width in the cell and \(L_{\text{drift}}\) is the distance between the cathode mesh and the top TGEM electrode.

Measurements with a calibration cell show that the photo-current reaches a plateau at \(T \geq 80^\circ\text{C}\). The QE of EF in full absorption (the region of the saturated photocurrent) is \(Q_{\text{sat}} \approx 20\%\) at 190 nm [6]. Vapor pressure of EF at 80°C and 40°C, are about 2 and 0.2 Torr, respectively. This gives \(Q_{\text{EF}} \approx 1\%\), see eq. (3.1). As can be seen from figure 8, the EF vapors at \(T = 40^\circ\text{C}\) and in 10 mm gap have, approximately, same efficiency as CuI in vacuum, therefore its QE at 185 nm is around \(Q_{\text{EF}} \approx 1\%\). In gas, due to photoelectron back scattering it is around 0.5%, which is in qualitative agreement with published data [32, 33].

![Figure 8](image-url)

**Figure 8.** Current measured from the TGEM/RETGEM operating in ionization chamber mode when illuminated at 185 nm. The length of the drift region was 1 cm. For comparison, the data obtained with EF vapor at temperature \(T = 40^\circ\text{C}\) is given.

In the next series of measurements, we checked the gain stability of the TGEM/RETGEM detector built. Measurements were performed in pure Ne (figure 9) at a pressure of 1 atm because in this gas the gain value at fixed voltage is known to be very sensitive to tiny amount of impurities. Therefore, Ne is very convenient to monitor possible outgassing of the chamber. In fact, we observed some charging up effect, likely due to the long-time outgassing which causes TGEM/RETGEM over-drying.

In mixtures of Ne with quencher gases much higher gains are achieved. As an example, in figure 10 the gas gain in Ne+5%CO\(_2\) is presented. A sufficiently high gas gain is an important factor in achieving a single photoelectron detection efficiency close to 100%. Indeed, only pulses above
Figure 9. (Left) Effective gas gain of a TGEM/RETGEM ($t = 0.4$, $d = 0.5$, $s = 0.9$, $h = 0.1$ mm) in pure Ne. (Right) Gas gain fluctuations with an applied voltage of 325 V as a function of time. Gas gain is normalized to the first measured value.

Figure 10. Effective gas gain as a function of the applied voltage measured with a TGEM/RETGEM detector filled with Ne+5%CO$_2$.

the threshold defined by the electronic noise are detected. The single electron detection efficiency is given by:

$$\epsilon_{se} = \frac{\int_{S_{th}}^{\infty} f(S) \, dS}{\int_{0}^{\infty} f(S) \, dS}$$

(3.2)

where $f(S)$ is the signal amplitude distribution and $S_{th}$ is the value of the electronic threshold. Therefore, one of the possible way to achieve high efficiency is to operate the detector at the highest possible gain. Of course, with low noise electronics the gain where we reach efficiency close to 100% can be decreased. In mixtures of Ne with quencher gases, good long-term gain stability was observed at low counting rate already after 1–2 days of heating and pumping of the gas chamber and the short term charging up effect was less pronounced, probably because not all the moisture was removed from G-10 during this relatively short time of pumping. More experimental data related to TGEM/RETGEM stability can be found in ref. [11].
In figure 11 bare Cu and CuI QE, relative to bare Cu QE at 0°C, as a function of temperature are shown. In both cases, QE increases with temperature. This effect was observed earlier [43]; other solid photocathodes exhibit similar behavior [6, 33].

![Figure 11](image)

**Figure 11.** Relative QE, with respect to bare Cu at 0°C, of CuI and Cu photocathodes as a function of temperature.

From the presented data, assuming CuI QE at room temperature around 0.5%, it follows that the bare Cu has QE ≈ 0.015%, which is close to published data [44].

Figure 12 shows the number of counts per second detected by the TGEM/RETGEM detector as a function of the distance from the a candle of the same type previously used. For comparison the data obtained with Class-1 are also plotted. As it can be seen, the CuI-TGEM/RETGEM is roughly 100 time more sensitive with respect to the Class-1 detector, thanks to the large photosensitive area (≈ 100 cm²). In the same figure data for MWPC are also presented, that will be discussed in section 3.2.

On the same figure for all tested detectors the background counts produced by direct sunlight are shown as well. Using CuI-TGEM/RETGEM it is possible to detect flames from a candle on a distance of 15 m in direct sunlight conditions.

One of the advantages of TGEM/RETGEM detectors is the possibility of their optimization for a specific application. For example, in the case of a reflective CuI photocathode, the ratio of the diameter of the holes to their pitch, $d/s$, should be slightly decreased compared to the standard value used for the detection of charged particles in order to enlarge the sensitive area. At the same time, the drift field should be set to zero or even inverted, to improve the photoelectron capture into the holes.

### 3.2 Sealed multi-wire detectors

The ALICE collaboration at CERN developed and is using MWPCs combined with CsI photocathodes to detect Cherenkov photons (see ref. [5] and references therein). These detectors operate at a gas gain of about $5 \times 10^{4}$, have high QE in the UV region and are able to detect single photoelectrons.
Figure 12. Number of counts per second produced in various flame detectors as a function of their distance from a candle. Horizontal lines represent the background counting rate in direct sunlight conditions. Flat-
panel detectors are $20 \div 100$ times more sensitive than Class-1 detector. In the Class-1 detectors and in the
detectors discussed in this paper, the sensitivity per unit area is roughly the same, and the main differences
in performance are due to the different photocathode active areas.

with an efficiency close to 95%. Based on this experience, as an alternative option to GEM-based
detectors, we developed a miniature version of this device to detect flames and sparks.

3.2.1 Setup

The design of the MWPC studied is shown schematically in figure 13. It includes two G-10 rings and
a G-10 disk. The latter has a metallized surface and serves as photocathode substrate. The effective
area of photosensitive layers of CuI or Ni is 33 cm$^2$. The two others rings are supporting frames for
stretched anode wires and the upper cathode mesh. All rings have grooves in their inner surfaces
to minimize current leakage. Due to this feature this design allows to reach high gas gains, enough
to detect single photoelectrons. The MWPC detectors are mounted inside a stainless steel vessel,
having a quartz window and feed throughs for supplying detectors with HV and taking signals from
them (figure 11 and figure 12). For the system outgassing, the chamber and the appropriate part
of the gas system is heated to about 150°C with electric heating tapes wrapped to Al (in order to
distribute heat uniformly). In these conditions the chamber is pumped for several days to obtain
a vacuum better than $10^{-6}$ Torr. After that, 80%Ar + 20%CO$_2$ gas mixture at pressure of 1 atm is
introduced.

It is worth to mention that later on we observed that the removal of the chamber outgassing
with a primary pump is sufficient, if quencher gases are then introduced inside.

To test the sealed detector at various temperatures, measurements at low temperatures were
done by immersing the test chamber into a bath filled with ice or dry ice. For measurements at
temperatures above 20°C, electric heating tapes were used.
3.2.2 Test results

As previously described, Ni and CuI photocathodes are solar blind, therefore they do not require the use of filters in case of outdoor applications. They have much lower sensitivity than CsI photocathodes, however it is possible to compensate this by using a larger surface. Moreover, due to the reduced photon feedback effect (compared to CsI), one can operate MWPCs at a higher gas gain, reaching about $10^5$ without any breakdowns (figure 14), which allows for achieving almost a 100% photoelectron detection efficiency.

In figure 12 the counting rate obtained from MWPCs with CuI and Ni photocathodes as function of their distance from the candle, is shown as well as the background counting rate caused by the direct sunlight. As can be seen, MWPC detectors are approximately 30 times more efficient than the Class-1 detector and the lowest background counting rate corresponds to the MWPC equipped with CuI. Note that the sensitivity per unit active area for GEM-based and MWPC detectors is the same, and the difference in the values reported in figure 12 is due to the smaller active area in the MWPC used for this specific test.

In figure 15 the relative sensitivities, $\mu_{\text{Ni}}$ and $\mu_{\text{CuI}}$, for sealed MWPCs combined with Ni and CuI photocathodes, respectively, with respect to Class-1 sensor, are shown as a function of time, to check their stability. In an analogous way as previously done, the presented values are calculated as follows:

$$
\mu_{\text{Ni}} = \frac{N_{\text{Ni}}}{N_{\text{Cl1}}}; \quad \mu_{\text{CuI}} = \frac{N_{\text{CuI}}}{N_{\text{Cl1}}}
$$

(3.3)

where $N_{\text{Ni}}$, $N_{\text{CuI}}$ and $N_{\text{Cl1}}$ are the number of counts recorded in the same time interval, with Ni, CuI MWPCs, and a reference Class-1 detector, respectively, when the candle is placed at a distance of 2 m from them.
Figure 14. Gas gain as a function of voltage for a MWPC, for two different gas mixtures. Due to the slits inside the inner surface of the rings, blocking the leaking current, it is possible to achieve high gas gain.

Figure 15. Relative sensitivities of a sealed MWPC combined with Ni and CuI photocathodes as a function of time with respect to a Class-1 detector, see eq. (3.3).

In figure 16 results of measurements of relative sensitivity of sealed MWPC at various temperatures are presented. As it can be seen, the detector operates stably in a wide temperature range, which is very important for outdoor applications. For comparison also the sensitivity of a 100 cm$^2$ TGEM/RETGEM detector is shown in the same figure. Again, the difference can be attributed mainly to the larger active area used. In fact, the ratio among the relative sensitivity shown in figure 16, is the same as the one shown in figure 12.

Although these results are encouraging, they should be considered as preliminary. We could not perform these measurements for long periods of time since the gas chamber was needed for other tests for our scientific program.
Figure 16. Relative sensitivities of a sealed MWPC with Ni and CuI photocathodes as a function of temperature with respect to a Class-1 detector. The isolated point at the top of the figure at 20°C corresponds to the CuI-TGEM/RETGEM.

3.3 Single-wire counter array

Manufacturing, even small, MWPCs is a time consuming process, requiring well trained technicians. Therefore, one can expects that commercial flame detectors based on multi-wire structures will be more expensive than single wire ones. Taking this into account, we developed a conceptual design of a simplified version of a prototype of a large area flame detector. It consists of an array of single wire counters, with rectangular Ni photocathodes (figure 17). The main simplification is that only four wires were used. They were stretched and soldered on a standard printed circuit board (PCB). This makes it much easier to manufacture than both single wire and the small pitch MWPC described above. The active area of 8×8 cm² makes it 64 times more sensitive than Class-1 detector. Another advantage of this approach is its larger angular acceptance (due to the rectangular cathode shape) which is a favorable factor for some applications. The gain as a function of voltage for this detector is presented in figure 18. As it can be seen, gains above $10^6$ can be achieved with this design ensuring single photoelectron detection efficiency close to 100%.

Figure 17. A schematic design of an array of rectangular single wire counters with Ni photocathodes.
3.4 Detector comparison

The main advantages of TGEM/RETGEM detectors are that they are commercially available and are able to provide UV visualization. However, for efficient single photoelectron detection (for the case of continuous flame) a multistep configuration is needed, which makes the detector more complicated and expensive. Moreover, they are suffering from occasional spark-type discharges, which appear above the Raether limit [45] and that may harm the detector. On the other hand, MWPCs do not present destructive discharge problems (note that in correctly designed wire type detectors discharges appear not at the Raether limit but at some critical gas gain due to the feedback mechanism [45]. This phenomenon does not lead to sparks but to “mild” corona discharges, with a typical current of some μA, which does not destroy the detector), and this amplification structure may have some advantages for commercial flame sensors application. If fine segmented readout electronics is not required (as in the case of flame detectors without imaging capability) the array of single wire detectors may represent a simple, cost effective solution.

4 Flat-panel sensors able to detect simultaneously flames and smoke

As already mentioned in section 1, the important advantage of the detectors presented in this paper is that they can operate in proportional mode, with the signal proportional to $n_0$, the number of photoelectrons produced within typical signal duration, about 1 μs in our case. High sensitivity to single primary electron ($n_0 = 1$) is crucial in order to detect fires at the earliest possible stage of their development. Operating the detector in proportional mode opens up the possibility to discriminate among flame, sparks and cosmic rays: a train of low amplitude pulses, corresponding to the detection of single photons, will be the signature of a starting fire while the burst of photons produced by a spark will give raise to a clear higher amplitude signal, limited to a short time interval (typically microsecond). Cosmic rays will mimic sparks, due to their intrinsic $n_0 \gg 1$, but they can be discriminated putting two or more sensors in coincidence.
Proportional mode offers another unique possibility: to detect simultaneously flames and smoke. Such an apparatus is schematically shown in figure 19. It contains a flame detector, and a pulsed UV source. In preliminary tests, a miniature D$_2$ lamp was used producing periodical UV pulses with a duration of about 10 ns at FWHM. Its emission spectrum is typical of any D$_2$ lamp; it has a molecular peak at 160 nm and a continuum in the region 200–300 nm. Due to the absorption in the air, only radiation with $\lambda > 180$ nm can reach the detector.

The operation principle of the smoke principle is illustrated in figure 19. The UV light periodically generates pulses of large amplitude ($n_0 \gg 1$). At the same time the detector is able to record pulses with $n_0 = 1$, produced by the flame (if they occur). If there is smoke (or any other obstacle) on the way of the UV light, it causes its attenuation and the amplitude of the recorded periodical pulses decreases, which can be used to trigger the alarm signal.

In figure 20 and in ref. [11] some experimental data are presented. In these measurements the D$_2$ lamp is placed 4.5 m away from the detector. Although the intensity of the lamp is very low (it can hardly seen by eyes even at 25 cm and in full darkness), it produced $n_0 \approx 10$. In ref. [46] one can find a video showing experiments with this flame and smoke detector. When the D$_2$ lamp is placed in the focal plane of a lens, the distance is increased up to 10 m.

With a much more powerful Xe pulsed lamp (Hamamatsu lamp L7685), combined with a lens, the monitoring distance could be increased by an order of magnitude. With such UV lamp, with a beam splitter made of optical fibers, one could monitor a large area of interest in various directions and angles.
5 Conclusions

In this work, we presented results about the development and evaluation of prototypes of sealed flat-panel flame and spark detectors, for indoor and outdoor applications. Preliminary tests show that they are able to operate stably in the temperature range \([-60^\circ C, +90^\circ C]\), with a detection efficiency up to about 120 times higher than that of the best Class-1 commercial sensors. This becomes possible after studying various double-layer and single-layer solar blind photocathodes and selecting among them the most suitable for these applications: CuI and Ni. Of course, for commercial applications the stability of operation should be demonstrated on a period of time of months/years.

One goal of our studies was also to investigate the possibility to use GEM-based detectors. The results obtained have proven that TGEM/RETGEM sealed detectors of flames can be manufactured, and their stability in time looks promising. This opens the possibility to use them as commercial flame detectors. In the Class-1 detectors and in the detectors discussed in this paper, the sensitivity per unit area is roughly the same, and the main differences in performance are due to the different photocathode active areas. In this context, the use of flat-panels is a big advantage and allows improvement in performance up to two order of magnitude. Note that in the commercial flame sensors, based on gaseous detectors, it is not possible to increase their active area due to the physical process of their operation (glow discharge). Moreover, in a sophisticated flame monitoring system, one can exploit their imaging capability [13, 42, 47, 48], which will allow not only to visualize flames, sparks and smoke, but also determine their position in space. Combined with a pulsed UV source they can be used to detect smoke, indoor and outdoor.

As alternative, we also tested MWPC-based flat-panel detectors. The main advantages are:

- They do not need a gas pre-amplification structure, which simplifies the design and the voltage supplier scheme;
- MWPC does not have problems with discharges able to destroy the detector.
Therefore, it looks like that, besides TGEM/RETGEM option, MWPC or arrays of single-wire are also attractive options for the commercialization. We thus believe that the described technology is mature and ready for the industrialization stage.

Currently, with the help of our collaborators from CERN, we are preparing a front-end electronics to connect our detectors to the CERN Radiation and Environment Monitoring Unified Supervision (REMUS) system. A portable sealed detector with readout electronics and high-voltage powered by a battery is also under development in collaboration with companies.

The focus of our future work will be on converting the laboratory prototypes of our sensors to commercial one. This will require their designing, manufacturing and finally perform all tests required by commercialization protocols, including long term stability monitoring.

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