Ionic smoke sensor without radioactive source

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KEYWORDS : Smoke sensor, Ionic, Corona effect

Ionization smoke sensors are amongst the best smoke sensors; however the little radioactive source which they include is no longer desirable since recycling gets more complicated. In this paper we discus an electrostatic system in which corona phenomena is used to generate the ions needed to smoke detection. We show how the velocity of ions is reduced for a better interaction between smoke and drifting ions. Influence of smoke, temperature and moisture is studied. It is shown that the proposed sensor has a good sensitivity compared with conventional ionic smoke sensors and optical smoke sensors.

Manuscript received: November 30, 2010 / Accepted: January 17, 2011

NOMENCLATURE

U.S.A : United states of America
CPC : Central Product Classification
NFPA : National Fire Protection Association
EU : European Union
LED : Light Emitting Diode

1. Introduction

Smoke is the first indication of fire and it is really important to detect it as soon as possible in order to alert the inhabitants for stopping the fire or running away in time. The alarm of a smoke sensor is particularly important in case of nocturnal fires, since it can save the life of sleeping residents.

In 1890, inventors Francis Upton, who works with Thomas Edison and Fernando Dibble, created the first portable electric fire-alarm [1]. It was a temperature sensor consisting of a battery, bell, magnet and thermostatic device, which triggered an alarm when the temperature went over a certain predetermined temperature. Even if the cities were equipped by general temperature-based fire alarms at that time, Upton invented the first of its kind to operate apart from the centralized city's fire alarm system in order to be used in buildings out of the reach of the city fire department.

In 1930, Swiss physicist Walter Jaeger was working on a system to identify poisonous gases. That system generates ions, and he hoped that poisonous gas passing through the ionized air bind to them and change the electrical current measured due to ions. His experiment failed, but he observed that his system responded to the smoke of his cigarette. He noticed a drop in electrical current due to the smoke passage through his system, and opened a new way for the improvement of fire alarm technology [2, 3]. But it has been necessary to wait 30 years in order to obtain radioactive sources and effective circuits compatible with home applications.

In fact, the first truly low cost and easy to use home smoke sensor was invented by Duane D. Pearsall in 1965 [4]. He used battery as source of energy which was easy to install and to replace by the owner. Pearsall Company, Statitrol Corporation, was the first which began the mass production of the home smoke sensors in Lakewood, Colorado, and the first commercial smoke detectors came to market in 1969.

According to a survey in 2008, smoke alarms are installed in 96% of U.S.A homes. The evolution of smoke alarm installation is shown in Fig. 1 [5]. Most of them were ionization-type battery-operated detectors.

However based on CPC's field investigation, 20% of equipped homes had none of their alarm working so only 75% of homes have at least one working smoke alarm. Also it has been noticed that one smoke alarm is usually not enough in a house.

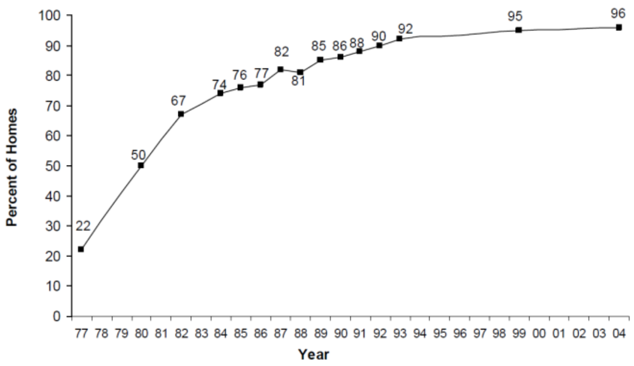

Fig. 1 Percentage of home smoke alarm installations from 1977 to 2004

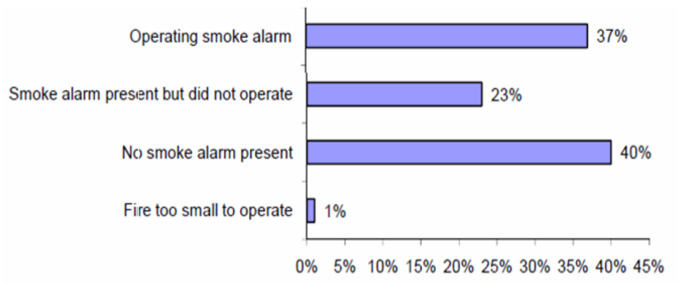

Fig. 2 Home Fire death percentage by smoke alarm performance

Fig. 2 shows the percentage of death due to home fire accidents by smoke alarm performance [5]. We see that 63% of home fire deaths occur in homes with no smoke alarm or no working smoke alarms. According to NFPA 2002, in the U.S.A, an inhabitant dies from fire every 156 minutes. It is estimated that if all of U.S.A houses were equipped with working smoke detectors, the residential fire death could drop by 36% (~1100 lives saved per year) [5]. It is a worldwide problem when we notice the number of fire deaths in other countries. Table 1 shows annual death number in the EU per million civilians according to statistics of European fire academy [6].

Luxembourg	2.8	Italy	12.8
Cyprus	4.0	Poland	13.2
Netherlands	4.1	Belgium	13.5
Spain	6.0	Denmark	14.3
Portugal	6.1	Ireland	14.5
Germany	7.3	Sweden	15.7
Slovakia	9.0	Bulgaria	16.0
Slovenia	9.7	Finland	16.5
Austria	9.8	Hungary	16.7
Greece	10.5	Romania	20.7
United Kingdom	10.8	Lithuania	62.9
Czech Republic	11.2	Latvia	114.4
France	11.8	Estonia	122.0

Table 1 Annual death number in the EU per million civilians

All these statistics show why in 1992 the readers of the *R&D Magazine*, selected home smoke alarms as one of the "30 Products that Changed Our Lives". There are also statistics showing that most of the industrial accidents are due to fire. For example Table 2 gives the situation in France where fire represent 51% of industrial accidents between 1992 and 2005 [7].

Total accident number	21765
Fire	51%
Scattering pollutant	47%
Explosions	5,3%
Dominos effects	3,2%

Table 2 Ratio of industrial accident in France between 1992 and 2005

2. Smoke detection

2.1 Fire

Fire is a very complex chemical process influenced by many factors that affect its growth, spread, and development. The physical shape and state of the fuel, the available oxygen, and the transmission of heat all play important roles in fire development. Though each fire is different, all fires follow similar behavior which provides a scientific basis for their detection.

2.1.1 Phenomena of combustion

We can represent the phenomena of combustion by the triangle of fire illustrated in Fig. 3.

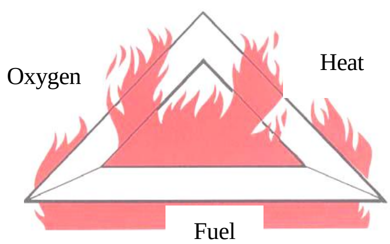

Fig. 3 Three elements necessary for a combustion reaction

Combustion is accompanied by the production of heat, light and new chemical species in different physical forms. Fuel is in the form of gas, liquid, or solid at the ambient temperature. But liquid and solid materials do not burn so the second element, heat, is needed to evaporate fuels. In fact, it is the vapor of fuel which burns. The primary source of oxygen, third element, normally is the air, which contains approximately 20.8% of oxygen. A concentration of at least 15 to 16% of oxygen is needed for the continuation of flaming combustion. Smoldering (pyrolysis) combustion can occur with as little as 8% of oxygen. A fire cycle depends in addition to proportioning, mixing, and ignition continuity [8]. All these elements are essential for both the initiation and continuation of the diffusion flame combustion process. When all of these elements are gathered, the reaction is triggered.

If the combustion is complete, the fuel burns in oxygen producing a limited number of products. In the case of hydrocarbons a complete combustion leads only to water and carbon dioxide exhausts. But in uncontrolled cases complete combustion is almost impossible because of oxygen defection or reaction quenched by a heat sink. As a consequence, smoke and unburned particles like soot or ash are produced as well as noxious gases like carbon monoxide.

2.1.2 Propagation of fire

The major part of calorific energy is evacuated by conduction, convection, radiation, and direct flame contact.

Heat radiation is a contactless way of transferring energy by generating infrared light. At about 1000℃, a temperature easily obtained during a fire, the amount of energy transmitted by radiation becomes very important. Conduction is the transfer of heat by direct contact through solid bodies. Convection is the transfer of heat by the displacement of mater, liquids or gases.

Convection is responsible for the transportation of smoke and unburned products during a combustion reaction. Hot smoke begins to rise up while cooling until the temperature homogenizes or until reaching the ceiling of the room. Then smoke spreads out. It is why smoke sensors are placed on the ceiling.

2.1.3 Classification of fires

Fires are classified by the types of materials that are burning. Class-A fires involve ordinary combustible materials, such as wood, clothes, paper, rubber, and many plastics. Class-B fires involve flammable or combustible liquids, greases, and gases. Class-C fires involve electrical equipments. Class-D fires involve combustible metals such as magnesium, titanium, zirconium, sodium, and potassium.

All fires produce combustion products which are divided into four categories: heat, gases (including carbon monoxide, hydrogen cyanide, ammonia, and hydrogen chloride), flame, and smoke particles produced by incomplete combustions (suspended in gases and vapors, or solid and liquid aerosols, soot, black particles of carbon) [9].

2.1.4 Fire sequence

A fire in a room or defined area generally progresses through three predictable developmental stages [10].

The first stage is called incipient stage (growth) and begins at the moment of ignition. The flames are localized and the fire propagation is regulated by the configuration, mass, and geometry of the fuel itself and not by the available oxygen. In this stage smoke may be produced. The oxygen content and temperature are in within the normal range.

In second stage more fuel is being consumed, and the fire is intensifying and spreading from the initial point by convection, conduction and direct flame. A hot and dense layer of smoke and fire gases goes up and begin to radiate heat downward.

The fire is still fuel regulated at this time. When the upper layer reaches a temperature of approximately 600℃, sufficient heat is generated to cause simultaneous ignition of all fuels in the room. This is called flashover and it is the third stage of the fire propagation. Once flashover has occurred, survival for more than a few seconds is impossible.

The length of time necessary for a fire to go from the incipient stage to flashover depends on the fuel, the room geometry, and ventilation. If the fire has been contained to a space, and the oxygen level drops below 15 to 16 percent, flaming combustion will stop even if unburned fuel is still present. At this point glowing combustion will take place. This stage is known as smoldering (decay) stage. High temperature and considerable quantities of soot and combustible fire gases have accumulated, and at this point the fire is oxygen regulated. If a source of oxygen is introduced, new ignitions are possible with explosive force. This phenomenon is known as a backdraft.

Various physical phenomena can be used for detecting fires. In early stage only ionic sensors provide sufficiently sensitive detection. At second stage, optical sensor can be used. These two kinds of sensors are smoke detectors.

2.2 Principe of existing smoke detectors

There are different types of smoke sensors. They can use light beams or electric charges in order to detect smoke. In some cases different measurement methods can be used to gain in efficiency, for instance for specific detection, but it is often at the expense of price.

In the case of smoke sensors based on light beams, two operating modes are currently implemented. In the first operating mode, smoke blocks the light between a laser diode and a phototransistor. The subsequent reduction of light reaching the phototransistor triggers the alarm. This type of sensors is usually used in large installation because sensitivity increases with distance between the emitter and receptor. In the second operating mode, which is the most commonly used, smoke diffuses light coming from a LED. The signal received by the phototransistor is then small in absence of smoke but large in its presence. When the scattered light reaches the phototransistor, the alarm is triggered.

Though optic smoke sensors respond very quickly to smouldering fires, first mode optic sensors are efficient only when there is a large distance between the laser and the phototransistor and second mode optic sensors are not efficient for detecting the combustion gases or dark smoke, which are the first sign of a fire.

Ionic smoke sensors are composed of a source of ionization for generating charges and a drift chamber in which charges can slowly drift between electrodes polarized at low voltage. That drift generates a measurable continuous electric current. When smoke particles enter the drift chamber, they attach to the charges, neutralize them or decrease their speed resulting in a large current drop between the electrodes. That latter large current drop triggers the alarm. Fig. 4 shows an ionic smoke sensor with a radioactive source of alpha particles for charge generation.

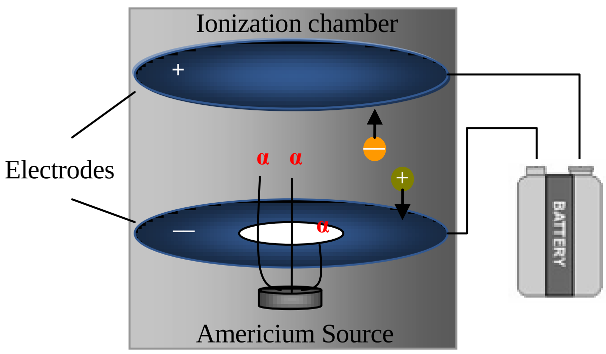

Fig. 4 Typical ionic sensor including an Americium source

Ionic sensors have a very good performance. They response more quickly to flaming fires. Also they are sensitive to less smoke amount than optical sensors. Moreover ionization sensors have a higher degree of security compared to optical sensors since the alarm intrinsically sounds when the battery starts to fail, warning that it is time to change it before the detector becomes ineffective.

2.3 Physical Principle of existing ionic sensors

2.3.1 Charge generation by a radioactive source

From the first ionic smoke sensors of 70's decade until the last most developed ones of our time, they are all made around of a radioactive source to generate ions. Usually a small quantity of americium-241 (Am-241) about m=0.3 µg which have a half-life ($t_{1/2}$) of 432 years, is used to generate alpha particles in the ionization chamber of the ionic smoke sensor. Equation (1) shows the alpha decay of Am-241 element. Energy released by the reaction is 5.7 MeV from which 5.6 MeV is taken by the alpha particles.

$$ {}^{241}_{95}Am \rightarrow {}^{237}_{93}Np + {}^{4}_{2}He \quad (1)$$

According to the percentage of nitrogen and oxygen in air the mean ionization potential of air is about I=95 eV. Each alpha particle released in the ionization chamber creates about 60000 free electrons in the chamber. Positively-charged oxygen and nitrogen ions are attracted to the negative electrode and the electrons are attracted to the positive one generating a small continuous electrical current. If the activity of Am-241 source is A_0, the generated current is:

$$i = A_0 \frac{E_\alpha}{I} \quad (2)$$

This current is typically of the order of a fraction of nanoamp, in absence of smoke particles.

2.3.2 Smoke particle charge interaction

When smoke particles enter in the ionization chamber, they are subjected to the electric field generated by electrodes but also to the one generated by the charges. Close to the charges, the electric field is highly divergent resulting in dielectrophoretic force acting on smoke particles. The force tends to bind the smoke particles to the charges. When smoke particles are considered as isotropic neutral dielectric bodies linearly and homogeneously polarisable, dielectrophoretic force F can be expressed as

$$F = \frac{1}{2}\alpha v \overrightarrow{grad}\left|E^2\right| \quad (3)$$

where α depends on smoke particle polarizability, v is the smoke particle volume and E is the electric field produced by the charges [11]. Coefficient α is typically of the order of $\varepsilon_0/3$ [12] where ε_0 is the dielectric constant of air. Volume v is approximately 4µm^3 for a 1-µm diameter smoke particle.

Amplitude of electric field E produced by charges is given by coulomb's law:

$$E = \frac{1}{4\pi\varepsilon_0}\frac{q}{r^2} \quad (4)$$

in which r is the distance between the charge and the smoke particle. Due to the divergence of the field, the dielectrophoretic force decrease as $1/r^5$. If a smoke particle is close to a charge then they can bind. If the smoke particle is relatively far from the charge, the time of interaction may be relatively long and it is necessary that the charge drifts sufficiently slowly in the chamber to optimize the interaction. Indeed if the charge passes too rapidly there will be not enough time for the smoke particle to bind and thus nothing would be detected. In fact the capture radius reduces with the electric field and is of the order of 10 µm for E=1 V/mm.

When the smoke particles attach to the free charges due to electrophoresis force, the charges become heavy bodies then the charge mobility μ decreases resulting in a drop of the electric current measured between the electrodes of the ionization chamber.

Even if ionic detectors are very efficient, according to new standards they are no longer authorised in almost all of the developed countries because of the radioactive sources they include for generating the ions. Such radioactive sources are indeed difficult to collect and to recycle. Therefore another ionization method is required to replace radioactive sources.

2.4 Alternative ion source

2.4.1 Corona effect

Corona effect is a discharge phenomenon which can be used to create charges in air. There are different possible corona configurations. In all of them, there is a sharp electrode under high voltage which generates an intense electric field capable to ionize surrounding air, and in front of it there is a relatively large electrode which collects charges due to ionization. The geometry used in our experiments is wire-plane. The voltage needed to ionize the molecules of air between the wire and the plate depends on different parameters such as the ionization energy, the gas pressure, the distance between the electrodes and their shape. There are numerous studies on corona properties either theoretically or experimentally [13].

During a corona discharge, space between the electrodes is divided in two distinct regions: (i) a high field ionization region surrounding the sharper electrode where the ions are created and (ii) a low field drift region occupying the remaining interval. Though corona phenomenon is a good way to generate a lot of ions, they drift so quickly that they cannot well interact with smoke particles. One solution to this problem is to separate ionization chamber in which the ions are generated by corona effect from drift chamber in which the ions could drift in a small uniform electric field sufficiently slowly to be able to interact with smoke particles.

2.4.2 System of measurement

In our system the ionization chamber consists of two electrodes under high voltage. Electric field is nonuniform because the electrode under high voltage is a small radius wire.

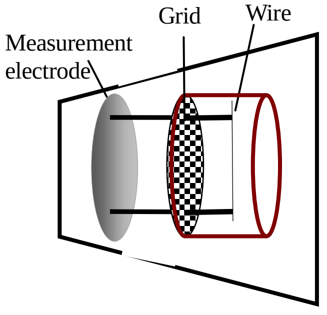

Fig. 5 Schema of ionic sensor

In order to slow the charges generated by corona effect in the drift chamber, we have used a grid electrode between the two chambers. That grid electrode is polarized to a low negative voltage. Charges are then collected by a measurement electrode which is grounded through an electrometer. This is illustrated in Fig. 5.

3. Analyses of the results

The wire under high voltage is made of gold coated tungsten and has a diameter of 25 μm. It is held under around -2.5 kV while the grid in front of it, is under -9 V. Electrons generated due to ionization of air in a small region around the wire are accelerated in direction of the grid which is made of brass wires of 0.3-mm diameter and 1-mm pitch. Some electrons are collected by the grid but others pass through the grid and enter to the drift chamber in which they drift gentely until arriving to the measuring electrode. The electric current measured is of the order of 1nA.

The sensor is placed near a source of smoke produced by combustion of either Amadou which is a spongy flammable substance prepared from bracket fungi, or a composition of dried flower and straw of Lavander. In Fig. 6 the granoulemetry of smoke particles is compared with the one of room particles.

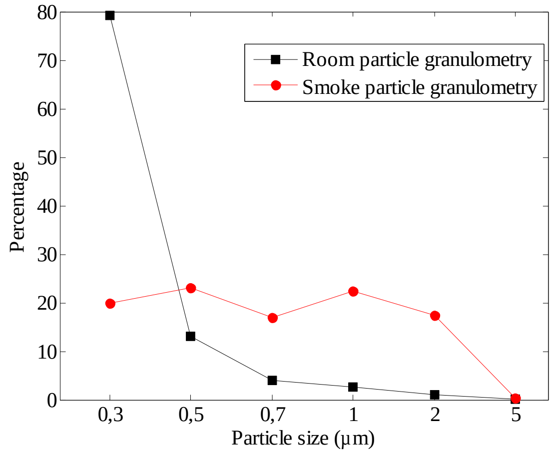

Fig. 6 Size grading of the smoke particles compared with the room particles

In this figure, the percentage of particles in different range of size is compared. The mean size of smoke particles is around 1μm while the one of room particles is around 0.3 μm.

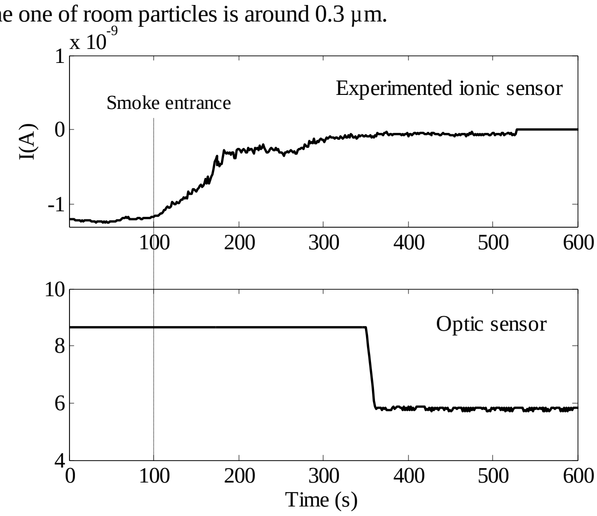

Fig. 7 Comparison between the response of the ionic sensor and an optic sensor

The alteration of electric current measured by our ionic sensor due to smoke entrance is shown in top of Fig. 7. As expected a large reduction of electric current due to smoke entrance to the sensor can be observes. The bottom part of this figure illustrates the response of an optic sensor which is installed close to our sensor. It reacts 150 seconds after our ionic sensor.

In Fig. 8 is shown the effect of the wire diameter on the result of the ionic sensor. Using a wire with a diameter of 10 μm instead of 25 μm affects significantly the amplitude of electric current in absence of smoke, by about one order of magnitude, while it does not affect the electric current in presence of smoke.

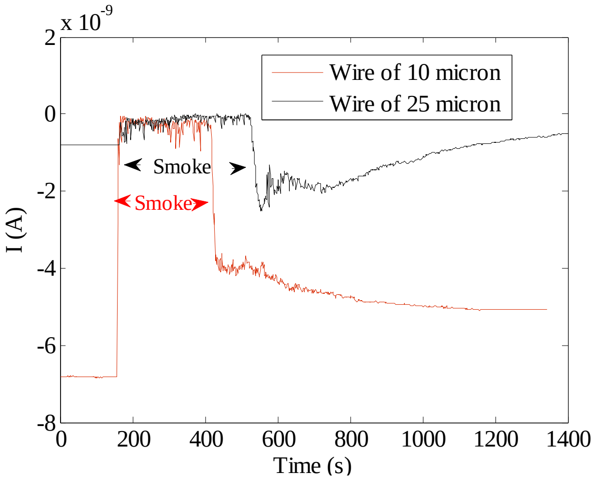

Fig. 8 Response of the ionic sensors with different wire diameter

This result can be explained by the effect of the sharpness of active electrode in corona phenomenon. As intensity of electric field around the active electrode depends on its sharpness, using a wire of smaller radius increases the electric field in air and at the same time the volume of ionization region so the number of electrons released in air. As a consequence the electric current measured in sensor increases. In our case the smaller is the wire the better is the sensor sensitivity. Another possibility is to reduce the applied voltage and thus the consummation for a given sensitivity.

The distance between the grid electrode and the measurement electrode also alters the sensor sensitivity. Fig. 9 shows the influence of two different heights of the chamber.

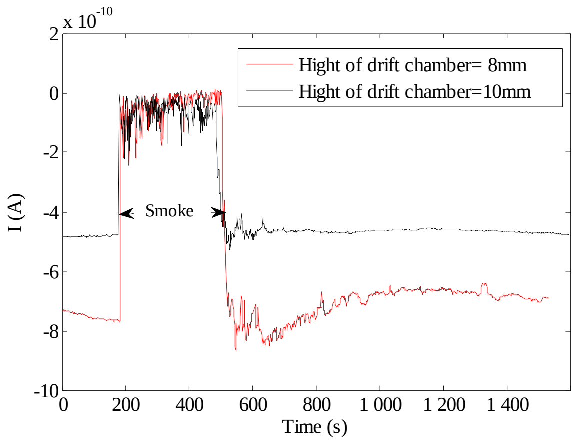

Fig.9 Response of the ionic sensors with different heights of drift chamber

As in the case of wire diameter, drift chamber height does not modify the electric current in presence of smoke particles but it affects the current when there is no smoke. One observes that in a drift chamber of 8-mm height, amplitude of electric current in absence of smoke is larger than in a drift chamber of 10-mm height. Reduction of the distance between the grid electrode and the measurement electrode increase the electric current because electrons drift in a larger electric field.

In order to prevent false alarms it is indispensible to verify the effect of other parameters such as temperature and moisture on the ionic sensor. Fig. 10 shows the effect of temperature. During the procedure, temperature increases from 25℃ up to 55℃ with a rate of 1℃/min. At the time notified in Fig. 10, temperature reaches 55℃ and remains for 2 hours. Tolerance of temperature is ±5℃ during the increase of temperature and ±2℃ after its stabilization.

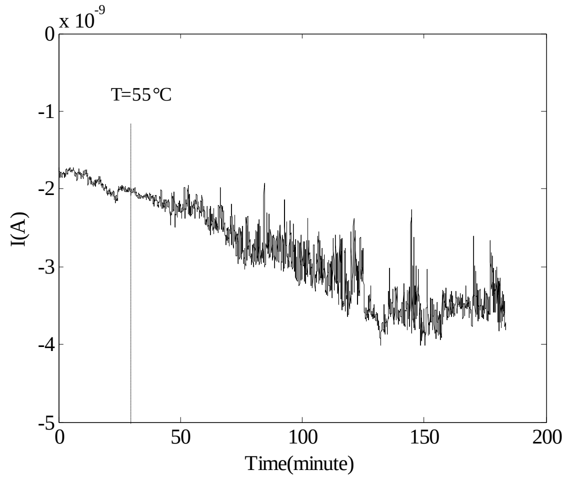

Fig. 10 Evolution of response of the ionic sensor with temperature

Electric current increases with temperature but since smoke produces a large reduction of electric current, the evolution of the current with temperature does not impair sensor detection.

Fig. 11 shows the evolution of the current when relative humidity at 40℃ varies from 40% to 70%.

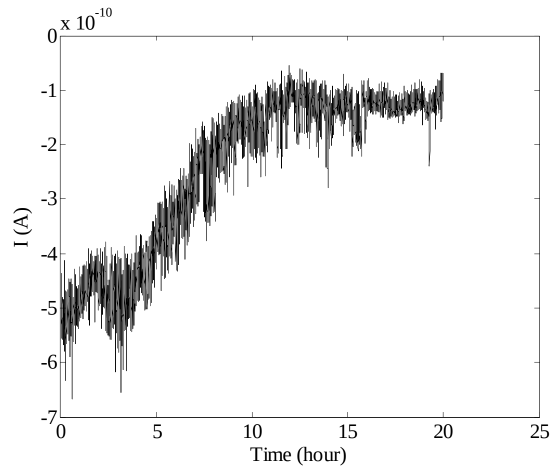

Fig. 11 Evolution of response of the ionic sensor with humidity

A high relative humidity causes a reduction of the measured electrical current. That variation is however relatively small compared to the one due to smoke. As for the temperature this variation does not impair sensor performance.

4. Conclusion

The radioactive source of ionic sensor has been replaced by a system based on corona effect with a wire electrode and a grid electrode for slowing the generated charges.

We have observed a repeatable reduction of the current due to the smoke particle entrance in the sensor. Also the response delay to the smoke is smaller than the one of optic sensors.

One observes that reducing the height of the drift chamber and diameter of the wire electrode, increases the difference between electric current without and with smoke particles. Less voltage on the active electrode is then possible which simplifies electronics and reduces the power consumption of the sensor. Thin sensors can be made with drift chamber as thin as some millimetres.

Temperature and humidity seems to do not affect the ionic sensor performance.

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