DETECTION OF CIGARETTE SMOKE USING A FIBER MEMBRANE FILMED WITH CARBON NANOPARTICLES AND A FRACTAL CURRENT LAW

by

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Cigarette smoke will cause irreversible damage to human health and living environment. It is especially important to accurately detect and effectively prevent cigarette smoke. This paper fabricates a fiber membrane filmed with carbon nanopowders as a smoke sensor. The experiment reveals that the fabricated membrane is sensitive to the smoke, two laws are proposed to model the current change of the sensor. Fractal calculus is used to exactly predict the current property at the initial stage, and a fractal modification of the current law is proposed. The present technology provides an economic way to mass-production of smoke sensors.

Key words: *cigarette smoke, carbon nanopowder, fabric, immersion method, nanoparticle, fractal calculus, variational principle*

Introduction

Smoking is harmful to the smokers and the environment, it can also cause a catastrophe like forest fires. The second-hand smoke is even more harmful, especially, to pregnant women and children. The number of deaths due to smoking per year is increasing and smoke-induced diseases, *e. g.*, lung cancer, coronary heart disease, asthma, oral cancer, and childhood diseases, are frequently reported on everyday TV news. In some important places, smoking is completely avoided, and effective monitoring of smoke becomes extremely urgent.

Though there are some technologies to detect smoke, among which the surface acoustic wave sensor for the third-hand smoke [1, 2], the passive detection method for smoking cessation [3], and smoke detection method for aircraft cargo compartment [4] have caught much attention. This paper suggests an economic and effective smoke sensor made of fabrics with a simple surface treatment.

Smoke sensor

Fabrics are everyday products, and burned ashes are available everywhere. We want to fabricate a smoke sensor using fabrics and ashes, the latter consists mainly of carbon parti-

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cles, which are used for surface treatment of the fabrics to improve conductivity. The immersion method [5] is used for the surface treatment: a fabric is immersed into an ash solution for few minutes, and a sensor is ready after removal of the surface water. In our experiment, we will use carbon nanoparticles instead of burned ashes in order to exactly reveal the mechanism for the sensor.

In our experiment, black non-woven fabric (Kong Jie Environmental Protection, Taizhou Gaoxin Nonwoven Fabric Co., Ltd.) and white cotton fabric (Guangzhou Nuosheng Nonwoven Products Co., Ltd.) were used as samples. The former is made of polyester with a carbon content of about 30%, the latter is made of cotton. The samples have length of 6.8 cm and width of 6 cm.

Carbon nanopowders (particle diameter 30 nm, Macklin C805116) were used for surface treatment of two samples. 3%, 6.25%, and 10% C-water solutions were prepared for experiment. Three pieces of each sample were immersed in the aforementioned three solutions for 10 seconds and then taken out. After 5 seconds for removal of surface water, the sample was wrapped with foil on both sides and clamped between two chucks, as shown in fig. 1. Cigarette smoke was produced under the sample as illustrated in fig. 2, we recorded the current change every 5 seconds. The current changes for two samples are given in fig. 3. The results show that our fabric sensors give a good response to smoke. A higher concentration of carbon solution results in a higher current because carbon nanoparticles can greatly improve the electrical conductivity of the sensor.

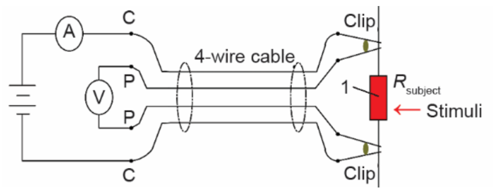

Figure 1. Measurement circuit. The resistor (1) is the sample, the stimuli are from smoke

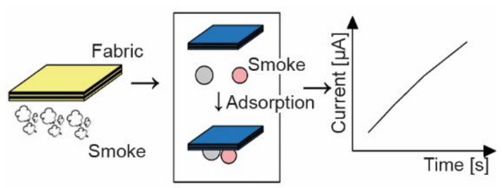

Figure 2. Smoke sensor

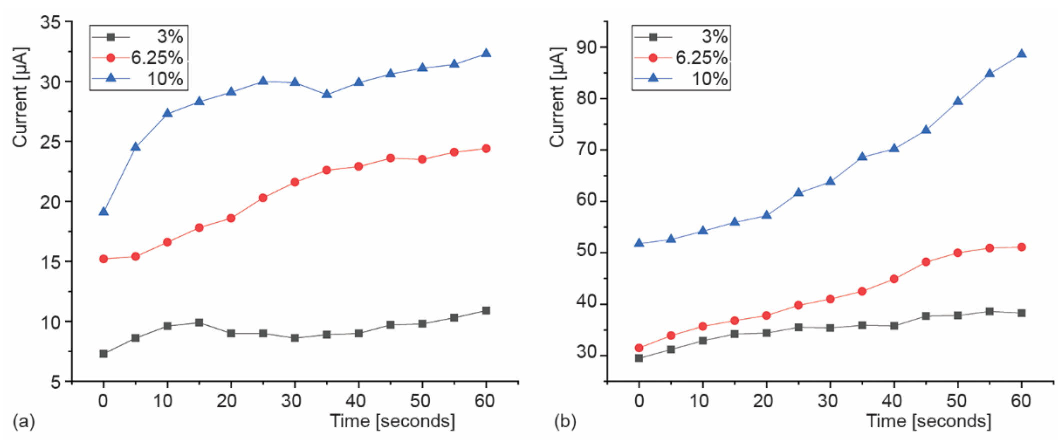

Figure 3. The current change; (a) sample 1 of black nonwoven fabric, (b) sample 2 of white cotton fabric

Theoretical analysis

Assuming that charge accumulated on the sensor is $q(t)$, we suggest the following current law:

$$\frac{\mathrm{d}I}{\mathrm{d}t} = k^2 q(t) \tag{1}$$

where I is current, q – the total charge, and k – a constant.

The current can be calculated by the following law:

$$\frac{\mathrm{d}q}{\mathrm{d}t} = \sum_{\mathrm{i}=1}^{N} c_i I^i \tag{2}$$

where c_i (i = 1~N) are constants.

We, therefore, obtain the following equation:

$$\frac{\mathrm{d}^2 I}{\mathrm{d}t^2} = k^2 \sum_{\mathrm{i}=0}^{N} c_i I^i \tag{3}$$

Considering the simplest case $c_i = 1$ and $N = 1$, we have:

$$\frac{\mathrm{d}^2 I}{\mathrm{d}t^2} = k^2 I \tag{4}$$

This equation leads to the solution:

$$I = I_0 \exp(kt) \tag{5}$$

We consider another case:

$$\frac{\mathrm{d}^2 I}{\mathrm{d}t^2} = k^2 (I + \mathrm{c}_3 I^3), \quad I(0) = I_0, \quad I'(0) = k^2 q(0) \tag{6}$$

This equation can be solved by the Taylor series method [6], the variational method [7-11], the variational iteration method [12, 13], and the homotopy perturbation method [14-16]. By the semi-inverse method [7-11], the variational formulation for eq. (6) reads:

$$J(I) = \int \left[\frac{1}{2} \left(\frac{\mathrm{d}I}{\mathrm{d}t} \right)^2 + k^2 \left(\frac{1}{2} I^2 + \frac{1}{4} \mathrm{c}_3 I^4 \right) \right] \mathrm{d}t \tag{7}$$

In case $c_3 < 0$, eq. (6) can be written in the form:

$$\frac{\mathrm{d}^2 I}{\mathrm{d}t^2} - k^2 I + C I^3 = 0 \tag{8}$$

where

$$C = -k^2 \mathrm{c}_3$$

When $-k^2 + (3/4)C > 0$, eq. (8) admits a periodic solution, this case should be avoided in the initial stage. The frequency-amplitude relationship can be easily obtained by He's frequency formulation [17, 18].

Discussion and conclusion

The initial current change is of great importance in practical applications. According to eq. (5), when $t \ll 1$, we have:

$$I = I_0(1+kt) \tag{9}$$

Actually in most cases, eq. (9) can be modified:

$$I = I_0(1+kt^\alpha) \tag{10}$$

where α is a constant.

The property given in eq. (10) can be modelled by fractal calculus [19-25], and the two current laws for the sensor can be modified:

$$\frac{\mathrm{d}I}{\mathrm{d}t^\alpha} = k^2 q(t) \tag{11}$$

and

$$I = \frac{\mathrm{d}q}{\mathrm{d}t^\alpha} \tag{12}$$

where $\mathrm{d}/\mathrm{d}t^\alpha$ is the fractal derivative [20]. Equation (4) can be modified:

$$\frac{\mathrm{d}^2 I}{\mathrm{d}t^{2\alpha}} = k^2 I \tag{13}$$

The two-scale transform [26, 27] can be used, and its solution can be obtained:

$$I = I_0 \exp(kt^\alpha) \tag{14}$$

Figure 4 shows that the fractal model given in eq. (10) is much more suitable for accurate detection than the linear model given in eq. (9).

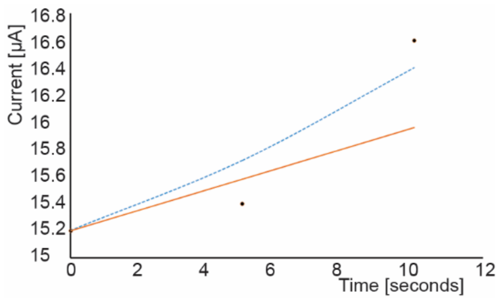

Figure 4. Comparison of the fractal model of eq. (10), discontinuous line, $I = 15.2(1 + 0.005t^{1.2})$, with the linear model of eq. (9), continuous line, $I = 15.2(1 + 0.005t)$, for the initial detection for 6.25% carbon/water solution of the Sample 1

A higher value of α is much needed in practical applications, and we have two ways for this purpose. One is to use nanofiber membrane, which can be produced by electrospinning [28-35], the other is to use a carbon solution with high concentration.

We have successfully fabricated a simple sensor using a fiber membrane to detect smoke. The method is simple in operation, and can be found wide applications due to its economical fabrication process and highly sensitive to smoke. Our technology is equivalently effective for detection of air pollution, especially, microparticles in the gas, and other nanoparticles, like PbSe nanoparticles [36] and copper and silver nanoparticles [37] might be more effective.

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