

Development of Noise Measurements. Part 5. Miniature Gas Sensors and their Performance

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Abstract: This work is devoted to the study of the impact of fluctuation parameters on forming random error of temperature measurements of environment. That is particular value for gas fire alarm sensors because it facilitates of increase of their data reliability. Random error is demonstrated to increase significantly under the decrease of sensitive element dimensions that, however, is demanded for reduction of sensor thermal inertia constant. *Copyright © 2013 IFSA.*

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1. Introduction

Standard EN 54 [1] regulates the reduction in 10 times – from 10 minutes to 1 minute – of operating time of fire alarm systems. It makes possible to withdraw the notion “fire” out of usage. Having reduced arrival time at the scene of action to such extent firemen have to deal only with “hotbed of fire”.

There are several ways of achievement of significant operating time reduction. The first way is transfer from non-addressable to addressable alarm systems. The second way is specified by the transfer to analogue sensors in which sensitive elements produce constantly signals linked with temperature or other environment parameter. The third way consists in usage of soft technical means for continuous processing of signal received from sensitive element, and elaborating of signals “Fire”, “Alarm” or others on the basis of analysis of character change.

In this case a few problems appear from one side concerning attempts to reduce sensor operating time that demands its miniaturization, and from another side regarding providing errorless operation [2]. The last one specifies necessity to provide high relation “signal-noise” and to increase the reliability of feeding signals “Fire”, “Alarm” under the low ratio “signal-noise”.

Gas as the object of study plays the role of thermosensitive substance which under volume contraction demonstrates fluctuation properties and it specifies sensor metrological parameters.

2. Goal of Work

The main goal of this work is the study of the gas sensor miniaturization impact on its metrological parameters.

3. Gas Fire Sensors

Producer companies give much attention to fire alarm sensors with sensitive elements produced in the shape of quasi-closed gas-filled chamber [3] (as example a fire sensor ADW 511A). One of the chamber surfaces is produced in the form of movable membrane that closes electric contacts during bending (Fig. 1). The chamber is equipped by the calibrated hole for pressure balancing inside and outside of it under atmospheric variation that eliminates the possibility of incorrect triggering. The membrane position depends on the pressure inside chamber. It helps to detect the temperature jump or its change accordingly to speed – 30 °C/30 seconds that indicates of fire [4].

In outgoing state and under slow temperature increasing inside-chamber-pressure and outside-pressure are balanced by means of excess gas yield through calibrated hole. Under rapid temperature change the air expands in the chamber but more quickly than it can get out through calibrated hole. In the case of fire when the gas in chamber heats quickly and membrane changes its position and closes contacts, the sensor in turn sends signals “Alarm” or “Fire”.

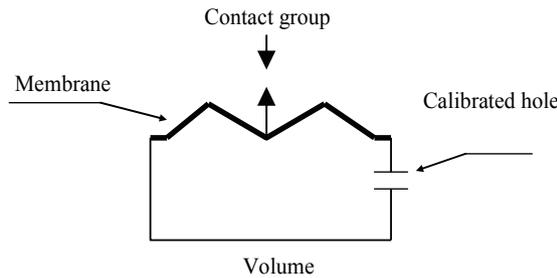


Fig. 1. Design of gas fire sensor.

Size decreasing of gas sensitive elements results into changing of operating gas volume. In consequence of it the impact of volume fluctuation on measurement result is increasing. In such case dominants can be next two components of measurement error: the first component determined by volume fluctuation of sensitive element, and the second component determined by thermal conduction fluctuation from controlling gas environment of fire to gas inside the chamber.

Determination of these components can be done by the next way. Heat transfer from fire source through the wall to thermosensitive substance of sensor (Fig. 2) which is the gas of specific composition can be described by well-known formula $Q = C_w m (T_2 - T_1)$, where C_w ; m is the heat capacity and chamber wall mass; T_1 is the temperature inside chamber; T_2 is the temperature of environment. Fluctuations of mentioned temperatures indicated as ΔT_1 ; ΔT_2 lead to forming of fluctuation

of heat quantity ΔQ that transfers through the chamber wall. So we can use next formula:

$$Q \pm \Delta Q = C_w m [(T_2 \pm \Delta T_2) - (T_1 \pm \Delta T_1)] \quad (1)$$

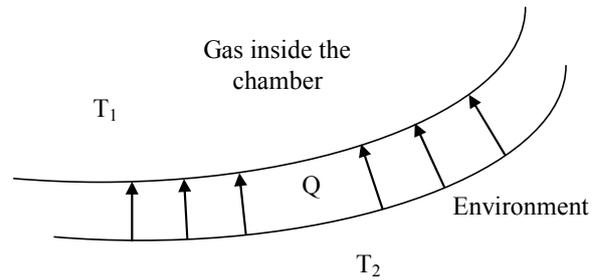


Fig. 2. Heat transfer from controlling environment to thermosensitive substance of sensor.

If average values of temperature, heat quantity and heat capacity are constants then heat quantity dispersion will be equal to:

$$D[Q] = D[C_w m (T_2 - T_1)] = C_w m D[T_2 - T_1] \quad (2)$$

Taking into account that linear combination dispersion of accidental non-correlated constants is equal to sum of dispersion items [5] then the formula (2) can be shown:

$$D[Q] = C_w m D[T_2] + C_w m D[T_1], \quad (3)$$

Considering the chamber of sensor is filled with ideal gas the pressure in it will be described by ideal gas formula [6]: $p = \frac{RT}{V_\mu}$, where p is the pressure, V_μ is the molar volume, T is the absolute temperature, R is the universal gas constant, or by an ideal gas law formula: $p = \frac{k_B N T}{V}$, where $V = \nu V_\mu$ is the volume; ν is the quantity of substance; k_B is the Boltzmann constant; N is the number of gas molecules in volume.

If this gas volume is considered as conditionally constant (Charles law) then we can use next equation:

$$\frac{p}{T} = \frac{p + \Delta p_i}{T + \Delta T_i}, \quad (4)$$

where Δp_i is the pressure increment and ΔT_i is the temperature increment in i moment of time. On the basis of (4) the link between pressure increment and temperature increment can be described by the equation:

$$\Delta p_i = \frac{p}{T} \Delta T_i, \quad (5)$$

which with consideration of ideal gas law formula can be shown as:

$$\Delta p_i = \frac{k_B N}{V} \Delta T_i, \quad (6)$$

In accordance with [6] relative root-mean-square deviation of pressure is inversely proportional to square root of quantity of molecules:

$$\delta\sigma[p] \sim \pm \frac{1}{\sqrt{N}}, \quad (7)$$

Taking into consideration (5) then accidental increments of temperature due to increments of pressure will be:

$$\Delta T_i = \frac{V}{k_B N} \Delta p_i, \quad (8)$$

Temperature dispersion specified by accidental pressure changes can be described by the next formula:

$$D[T] = \frac{1}{n} \sum_{i=1}^n (T_i - M[T])^2, \quad (9)$$

where n is the number of accidental temperature values; $T_i = M[T] \pm \Delta T_i$ is the temperature value in the i moment of time, $M[T]$ is the mathematical expectation (average value) of temperature.

In the case if $M[T] = const$ with consideration of (8) then it can be written:

$$\begin{aligned} D[T] &= \frac{1}{n} \sum_{i=1}^n \Delta T_i^2 = M[\Delta T^2] = \\ &= M\left[\frac{V^2}{k_B^2 N^2} \Delta p^2\right] = \frac{V^2}{k_B^2 N^2} M[\Delta p^2], \end{aligned} \quad (10)$$

When average value of pressure $M[p] = const$ then dependence of temperature dispersion on pressure dispersion can be determined from (10):

$$D[T] = \frac{V^2}{k_B^2 N^2} D[p], \quad (11)$$

as also root-mean-square deviation:

$$\sigma[T] = \frac{V}{k_B N} \sigma[p], \quad (12)$$

Having received from an ideal gas law formula the temperature value and taking into account (7) it can be concluded that relative root-mean-square deviation of temperature is inversely proportional to

square root to the quantity of gas N molecules in the chamber of sensitive element:

$$\delta\sigma[T] = \pm \frac{\sigma[T]}{T} = \pm \frac{\sigma[p]}{p} = \pm \delta\sigma[p] \sim \pm \frac{1}{\sqrt{N}} \quad (13)$$

Taking into account (13) temperature dispersion T_1 and T_2 can be written by following way:

$$D[T_1] = \frac{T_1^2}{N_1}, \quad D[T_2] = \frac{T_2^2}{N_2}, \quad (14)$$

So far as volume of controlling gas environment exceeds very significantly (in 10 orders of magnitude and even more) the volume of thermosensitive gas substance then N_2 is more larger than N_1 and temperature fluctuations of environment practically don't impact on dispersion of heat quantity. Therefore (3) can be shown as:

$$D[Q] = C_w m D[T_1] = C_w m \frac{T_1^2}{N_1}, \quad (15)$$

So random error of temperature measurement by means of the gas sensor is determined only by volume of its gas thermosensitive substance. It decreases to null if quantity of molecules (volume) of this substance increase, and vice versa it increases if volume decreases.

As volume of thermosensitive substance of fire sensor sensitive element is mainly known and using of certain Avogadro number ($N_A = 6,02 \times 10^{23}$ molecules per 1 mole of gas that occupies 22,4 l under atmospheric pressure) enables to modify equation (15) into engineering equation with indication of numbers of gas moles n in sensor sensitive element:

$$D[Q] = C_w m \frac{T_1^2}{n N_A}, \quad (16)$$

Taking into account that 1 gas mole occupies the volume of 22.4 l under normal conditions then in the case of conversion to standard units of volume the next formula can be used $n = \frac{V}{22,4}$, where V is the concrete value of gas volume that is determined in m^3 . Then (16) will take the next form:

$$D[Q] = C_w m \frac{T_1^2}{N_A} \frac{22,4}{V}, \quad (17)$$

Calculation of error that is specified by decreasing sensitive element chamber dimension can be done by the impact of temperature fluctuations or of heat quantity fluctuations.

Root-mean-square deviation of heat quantity as function of chamber volume of sensor sensitive element will be:

$$\sigma[Q] = \pm T_1 \sqrt{\frac{22,4 C_w m}{V N_A}}, \quad (18)$$

and relative root-mean-square deviation will be equal to:

$$\delta\sigma[Q] = \pm \frac{\sigma[Q]}{Q} = \pm \frac{T_1}{T_2 - T_1} \sqrt{\frac{22,4}{C_w m V N_A}}, \quad (19)$$

Having substituted value of constants in (19) the equation will be simplified to the following:

$$\delta\sigma[Q] = \pm \frac{6.1 \cdot 10^{-12} T_1}{T_2 - T_1} \sqrt{\frac{1}{C_w m V}}, \quad (20)$$

Study results of dependence of relative root-mean-square deviations of heat quantity on the volume of sensor element under different mass indexes of its copper walls are demonstrated in the Fig. 3.

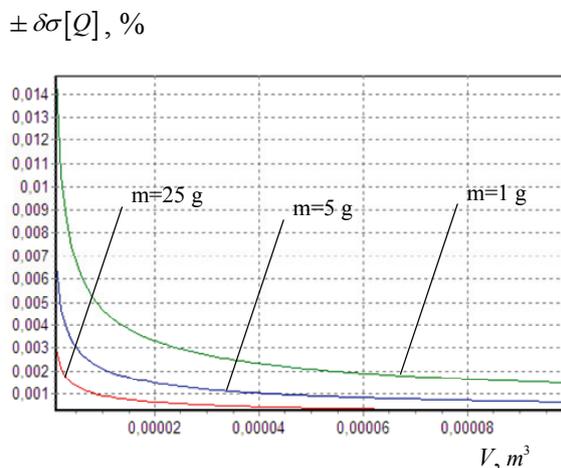


Fig. 3. Dependence of relative root-mean-square deviations of heat quantity $\delta\sigma[Q]$ on the volume V of sensor sensitive element.

Offered formulas enable to calculate the value of random error depending on volume of sensitive element chamber and sensor mass or to calculate the parameters of chamber by means of random error value which is given beforehand.

In the Fig. 3 is demonstrated that under significant decrease of fire sensor sensitive element dimensions (to 4 ml) – relative root-mean-square deviation increases to $\pm 0,007\%$.

Such value of random error is absolutely admissible for fire technology. For these sensor sizes the thermal inertia constant doesn't exceed 1 s.

Mentioned above is concerning exceptionally the estimation of value of random error of temperature control by means of gas-filled chamber. But in this case other possible components of temperature measurement errors are left out of account.

So with retooling of fire installations by small fire sensors the role of fluctuation deviations significantly increases in indications of measuring devices that are discovered in increase of their root-mean-square deviations and accordingly random errors.

4. Conclusions

The presence of properties fluctuations of control, gauge and signalization sensors establishes principal line of accuracy of any realized measurements that is special important for small size sensitive elements and demonstrated in the example of different size fire sensors.

In the case of small size gas sensitive elements (chamber's volume ~ 20 ml) relative root-mean-square deviations of heat quantity received by the chamber of sensitive element from the environment can be $\pm 0,0005 \dots \pm 0,0035\%$ depending on mass of its walls.

A random error of temperature measurement that is specified by the dimension effect increases significantly under volume contraction of chamber and mass of its walls.

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