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Magnetic Sensors of Oxygen Concentration

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Summary:

The analysis of the influence of the size of the oxygen sensor of thermomagnetic type to the performace of the sensor is carried out. It is shown that the necessary condition of the independence of the sensor response from the orientation of the sensor consists in the minimization of natural convection of air compared to the gas diffusion. The optimal size of the sensor is defined by fundamental constants of the gas medium.

Keywords: Oxygen, magnetic sensor, size effects.

Introduction

Detection of oxygen concentrations is vital in our everyday life, industrial and home safety, monitoring of technological processes and in many other fields of human activity. There three different ranges of this oxygen detection. The first one is the determination of oxygen in ambient air at concentrations close to 21 % (normal content of oxygen in air), the second is the determination of low concentrations of oxygen in inert gas, and the third is the detection of low concentrations of oxygen at low residual pressure in vacuum installations. Respectively, these three ranges require the application of different gas sensors. In addition, some of the applications, for example the measurement of oxygen in medicine, need very fast measurement of oxygen concentration with response time exceeding respiration rate (up to 100 respirations per minute).

The most known sensors used for the measurement of oxygen concentrations are the sensors of electrochemical type. These are the amperometric sensors with platinum working electrode and silver chloride reference electrode. The silver of the electrode is consumed in the process, and this limits the lifetime of the sensor. To improve this parameter, the sensors of Oxonium company (St. Petersburg) [1] restrict electrochemical current and use built-in amplifier; this permits to reach lifetime of the sensor up to 10 years.

Another type of the sensor used for ambient concentrations of oxygen is the sensor of magnetic type, which is the main topic of this work. Oxygen is the only paramagnetic gas (except NO), and this property lies in the basis of such type of gas sensors. Therefore, its concentration can be determined in two ways: using so-called "magnetic wind" resulting in the motion of oxygen-containing gas (air) in a gradient of magnetic field and gradient of temperature and using Senftleben effect, change in the diffusion cross-section of the triplet oxygen molecules in magnetic field. Magnetic field leads to precession of oxygen molecules and to decrease in heat conductivity of gas. This effect depends on the ratio of magnetic-field strength to gas pressure. Therefore, this type of gas sensor is applicable at low pressure of gas in a range 0.01 – 2 Torr. The threshold of O_2 detection is of about 10^{-5} Torr. This type of gas sensor can be used as used for the determination of oxygen concentration and, as well, as a leakage detection to a vacuum setup [2].

Model

Magnetic sensor of oxygen consists of a tube made of diamagnetic material placed in magnetic field of permanent magnet. This tube is equipped with heater and thermoanemometer measuring gas flow through the tube. Oxygen containing gas is attracted by magnetic field, on the other hand, magnetic susceptibility of this paramagnetic gas is reverse proportional to the square of magnetic-field strength. Therefore, if the gas is heated in the tube, the gradient of temperature leads to asymmetry of the system and to a permanent flow of gas in the direction from cold part to hot part of the system.

A very important advantage of this type gas sensor is a possibility to operate even in aggressive atmosphere. A disadvantage consists in the necessity to keep the orientation of the device because of competition between magnetic and natural convection due to a gradient of temperature.

To minimize this effect, it is necessary to consider the interference between the thermomagnetic and natural convection. The ideal condition for this is the situation, when the natural convection could be neglected and, therefore, when the thermomagnetic convection is independent of the orientation of the tube placed in magnetic field. In addition, to get response time sufficient for the measurement of oxygen concentration with characteristic time of < 10 ms, the dimension of the tube should be below a certain value defined by the diffusion processes.

Results about the influence of the microhotplate size to the convective heat exchange were obtained in [3]. Here we will use these data.

We considered the role of convection in the heat exchange of microhotplate. It was suggested that over microhotplate exists a virtual tube of upstreaming gas. In the case of recent work, this is real tube with diameter *d* and radius *r* heated up to temperature *T*. It is obvious, that the worst case, when the natural convection is most important compared to “magnetic wind” is a vertical orientation of this tube.

It was shown in [3] that the convection velocity of gas in this tube is equal to

$v = \frac{g\cdot\mu\cdot P\cdot r^2}{8\cdot\eta\cdot R}\left(\frac{1}{T_r}-\frac{1}{T}\right)$, where *g* is free fall acceleration, μ is mass of mole of gas, *P* – pressure, η – dynamic viscosity, *R* – gas constant, T_r – room temperature. Taking into account that $\eta = \nu\cdot\rho$, this could be rewritten as:

$v = \frac{g\cdot r^2\cdot T_{ev}}{8\cdot\nu}\left(\frac{1}{T_r}-\frac{1}{T}\right)$, where T_{ev} is everage temperature of gas. Convection can be neglected, if the time of the gas motion due to convection through the tube with length *h* is larger than the time of back diffusion of gas.

$\frac{h}{v} >> \frac{h^2}{D}$, or $v << \frac{D}{h}$; substituting previous formula to the last one, we obtain

$\frac{g\cdot r^2\cdot T_{ev}}{8\cdot\nu}\left(\frac{1}{T_r}-\frac{1}{T}\right) < \frac{D}{h}$, and

$r^2h << \frac{8D\cdot\nu}{g\cdot\left(\frac{T_{ev}}{T_r}-\frac{T_{ev}}{T}\right)}$, in our case $T_{ev}=T$, therefore

$r^2h << \frac{8D\cdot\nu}{g\cdot\left(\frac{T}{T_r}-1\right)}$; taking into account that both the values of diffusion coefficient and kinematic viscosity of air at working temperature of magnetic oxygen sensor are equal to about 2 cm^2/c, we can evaluate the dimension of the sensing element of gas sensor leading to the insensitivity of this element to the orientation of gas sensor in the gravitation field and, therefore, to its applicability in portable instruments.

Discussion

Let’s consider usual macroscopic gas sensors, that is a glass tube equipped with flow meter and put to magnetic field. If the diameter of this tube is, for example 0.1 cm, $T=2\cdot T_r$, the length of the tube should be by the order of magnitude $h<<3\cdot 10^{-2}/r^2 \sim 3$ cm. It is clear that the fabrication of such small sensor by macroscopic tools is rather complicated.

Our colleagues [4] made an attempt to fabricate this kind of gas sensor, which can be used in portable devices including medical instrument using microfabrication. The sensor was fabricated as a small spiral made of 10 μm Pt glass-coated wire. The spiral diameter was of about 100 μm, length was of about 150 μm. The spiral was suspended on two platinum wires in housing of TO-46 type and placed in a gradient of magnetic field. The orientation of the spiral in magnetic field was more or less random.

The results of [4] show that the thermomagnetic sensor can be used for the determination of oxygen concentrations from approximately 0.1 vol. %, the response time of the sensor is below 0.1 s, therefore it can be applied for medical monitoring. Results of recent work will be used to design advanced microelectronic version of the sensor of both thermomagnetic type and sensor based on Senftleben effect.

References

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