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Abstract

The Role of Convection and Size Effects in Sensor Microhotplate Heat Exchange †

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Abstract: The analysis of the influence of microhotplate size on the convective heat exchange of gas sen-sors is presented. It is demonstrated that there is a minimum size leading to the formation of convection heat exchange flow. Below this minimum, only the thermal conductivity of ambient air and IR radiation should be considered as channels for heat dissipation by microhotplate. This limit expression contains only fundamental constants of air, $d \sim 4 \cdot \sqrt[3]{\nu \cdot D / g}$, where ν is the kinematic viscosity of air, D is the diffusion coefficient, and g is the acceleration of free fall, d~0.5 cm.

Keywords: microhotplate; role of convection; heat losses; thermal conductivity

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1. Introduction

One of the common problems of the design of low-power consuming semiconductor and thermocatalytic gas sensors, as well as other sensors working at elevated temperatures (thermoconductometric sensors of gas concentration, air flow sensors, etc.), is the role of air convection in the cooling processes. In principle, convection could be important, because it leads not only to an increase in heat dissipation and an increase in power consumption but also to the influence of sensor orientation on the sensor response. Usually, in the simulation of heat exchange processes, it is suggested that only heat conductivity and radiation are the channels of heat losses. But it is difficult to find a pronounced estimation of a minimum size of microhotplate sufficient for the formation of convection flow.

It is clear that, if the size of the microhotplate is very small, the convection cannot start, because the expulsive force of air over the microhotplate is too low for this process. In this work, we try to estimate how small the sensor size should be to allow the neglect of the contribution of convection to the heat losses of the gas sensor.

2. Methods and Discussion

For the evaluation of the minimum size of microhotplate, which can generate an up-ascending air flow, we used the following assumptions. (1) There is a competition between two processes: the up-ascending air flow due to thermal convection and the backstream diffusion of air. If the convection of gas plays an important role in heat transfer, the characteristic time of convective transfer should be shorter than the time of diffusion. (2) The convective flow is laminar, and air in this flow is cooled due to heat conductance.

Let us consider a microhotplate with diameter d and radius $r = d/2$ (Figure 1). We suppose that there is a convection tube over this microhotplate, the temperature of the lower end of this tube is equal to the temperature of the microhotplate T, and the temperature of the upper end is equal to the room temperature Tr. The height of the tube is equal to h. The convection velocity of gas in the tube is v. The condition, which should be met to neglect convection, is

$$t > \tau \tag{1}$$

(t is convection time, τ is diffusion time) or $h/v > h^2/D$, D is diffusion coefficient.

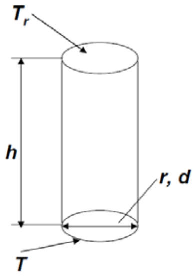

Figure 1. Microhotplate and convection tube over it.

The cooling time of gas in the tube is $\tau_1 = r^2/D$; therefore, the height of the tube is $h = v{\cdot}\tau_1 = \mathrm{v}{\cdot}r^2/D$. Formula (1) can be rewritten as

$$\frac{v{\cdot}r}{D} < 1 \tag{2}$$

The velocity of gas in the convection tube can be evaluated using Poiseuille formula

$$Q = \frac{\pi{\cdot}r^4}{8{\cdot}\eta{\cdot}h}{\cdot}\Delta P;\ \eta = \nu{\cdot}\rho; Q = \pi{\cdot}r^2{\cdot}v;\ \Longrightarrow\ v = \frac{r^2}{8{\cdot}\eta{\cdot}h}{\cdot}\Delta P$$

where ν—kinematic viscosity of air, η—dynamic viscosity, ρ—air density.

Taking into account the Archimedes' force acting onto the air in the convection tube, we can rewrite this expression as

$$v = \frac{r^2}{8\eta{\cdot}h}{\cdot}\Delta P = \frac{g{\cdot}\mu{\cdot}P{\cdot}h{\cdot}r^2}{8\eta{\cdot}h{\cdot}R}{\cdot}\left(\frac{1}{T_r} - \frac{1}{T}\right) = \frac{g{\cdot}\mu{\cdot}P{\cdot}h{\cdot}r^2}{8\eta{\cdot}R}{\cdot}\left(\frac{1}{T_r} - \frac{1}{T}\right) \tag{3}$$

Taking into consideration the ideal gas laws and relationship between kinematic and dynamic viscosity, expression (3) can be written as

$$v = \frac{g{\cdot}r^2{\cdot}T_{ev}}{8\nu}{\cdot}\left(\frac{1}{T_r} - \frac{1}{T}\right)$$

where T_{ev} is the average temperature in the convection tube.

Substituting this expression into Formula (2), it is possible to obtain the following limit for the microhotplate size.

$$\frac{g{\cdot}r^3}{8\nu{\cdot}D}{\cdot}\left(\frac{T_{ev}}{T_r} - \frac{T_{ev}}{T}\right) < 1 \quad or \quad r < \sqrt[3]{\frac{8\nu{\cdot}D}{g{\cdot}\left(\frac{T_{ev}}{T_r} - \frac{T_{ev}}{T}\right)}}$$

The cubic route of the term in brackets is close to unity under the usual conditions; therefore, generally, the convection part can be neglected, if the following condition is met

$$d < 4{\cdot}\sqrt[3]{\frac{\nu{\cdot}D}{g}}$$

This expression defines the conditions when only thermal conductivity and radiation should be taken into account for the estimation of heat losses of the microhotplate.

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