Modeling the distribution of temperature field within the micro heat-loss anemometer based on silicon carbide

D A Evstigneev 1, 2, V A Karachinov 1, A S Varshavskiy 1 and V A Manykhin 1

1 Division of Microelectronics, Novgorod State University, ul. B. St. Petersburgskaya, 41 173003 Veliky Novgorod, Russia
2 Email: Danya2allstars@yandex.ru

Abstract. The results of modeling the thermal characteristics of microsystems are presented and mutual thermal influence of the elements depending on the type of construction has been evaluated.

1. Introduction
The hot-wire method, based on the dependence of the electrical resistance of a temperature-sensitive element on the flow velocity of a liquid or gas, is widely used in various fields [1]. There are thermal microsystems that allow recording the velocity of high-temperature gas flows [2]. The basis of the construction of such microsystems is basically a beam structure, which from the point of view of the propagation of heat flows is not a losing option, and since the greatest interest at the present time is the speed and accuracy of measuring physical quantities, the need to create more advanced microsystems that meet these requirements will be at a high level. Reducing the heat flow, spreading from one element to another, increasing the performance indicators, these problems constantly require improvement of the design base. At the same time, continuous development of technology and a variety of operating conditions leads to the creation of designs of thermo anemometers of complex shape. An experiment is needed to carry out the design optimization study. But in view of the fact that it is not possible to carry out natural experiments due to the high cost of the material, the necessary stage of the study is the simulation of the thermal characteristics of the microsystem [3, 4]. The results of this simulation are presented in this article.

2. Research methodology
Heat–loss anemometer, which is a microsystem incorporating a thermometer, is made of silicon carbide 6H polytype with a concentration of uncompensated donors \( N_D = N_A \equiv 3 \cdot 10^{10} \, cm^{-3} \). The simulating process in the ANSYS environment was performed using the finite element method.

3. The results of the study and their discussions
The study of the thermal regime of the microsystem, in which the thermal bonds between the elements are determined mainly by the conduction process, the properties of the material and the design features, is a model analysis of the distribution of the temperature field from a strongly heated
element to a slightly heated one. For comparison, 2 variants of the design and the thermal model of the microsystem, presented in Figure. 1, are proposed.

![Thermal model of microsystem](image)

**Figure 1.** Thermal model of microsystem (a), microsystem design without hole (b), microsystem design with hole (c). 1 - the site of the heat-loss anemometer; 2 - the leg; 3 - the site of the thermometer.

We write down the original Navier-Stokes equations [6]:

\[
\begin{align*}
\rho \frac{Du}{Dt} &= X - \frac{\partial \rho}{\partial x} + \frac{\partial}{\partial x} \left[ \mu \left( \frac{2 \partial u}{\partial x} - \frac{2}{3} \operatorname{div} m \right) \right] + \frac{\partial}{\partial y} \left[ \mu \left( \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right) \right] + \frac{\partial}{\partial z} \left[ \mu \left( \frac{\partial u}{\partial z} + \frac{\partial w}{\partial x} \right) \right], \\
\rho \frac{Dv}{Dt} &= Y - \frac{\partial \rho}{\partial y} + \frac{\partial}{\partial y} \left[ \mu \left( \frac{2 \partial v}{\partial y} - \frac{2}{3} \operatorname{div} m \right) \right] + \frac{\partial}{\partial x} \left[ \mu \left( \frac{\partial v}{\partial x} + \frac{\partial w}{\partial y} \right) \right] + \frac{\partial}{\partial z} \left[ \mu \left( \frac{\partial v}{\partial z} + \frac{\partial w}{\partial y} \right) \right], \\
\rho \frac{Dw}{Dt} &= Z - \frac{\partial \rho}{\partial z} + \frac{\partial}{\partial z} \left[ \mu \left( \frac{2 \partial w}{\partial z} - \frac{2}{3} \operatorname{div} m \right) \right] + \frac{\partial}{\partial x} \left[ \mu \left( \frac{\partial w}{\partial x} + \frac{\partial u}{\partial z} \right) \right] + \frac{\partial}{\partial y} \left[ \mu \left( \frac{\partial w}{\partial y} + \frac{\partial u}{\partial z} \right) \right].
\end{align*}
\]

(1)

Here are the components of the velocity field in the x, y, z coordinate system; \( \rho \) - is the density; \( t \) - is the time constant.

To these equations, we must add the continuity equation, which in the expanded form has the following form:

\[
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u)}{\partial x} + \frac{\partial (\rho v)}{\partial y} + \frac{\partial (\rho w)}{\partial z} = 0,
\]

(2)

In addition to modeling with the help of equations (1) - (3) of heat diffusion in a fluid, heat transfer in solids is also modeled using the equation:

\[
\frac{\partial \rho \cdot e}{\partial t} = \frac{\partial}{\partial x_i} \left( \lambda \frac{\partial T}{\partial x_i} \right) + Q_n
\]

(3)

Where \( e = c \cdot T \) (c is the specific heat; T-temperature); \( \lambda \) - thermal conductivity; \( Q_n \) - specific (per unit volume) heat release of the heat source.
Convective heat exchange between the surface of solids and the fluid is simulated when modeling the boundary layer of the fluid flow.

The radiating surfaces are defined by absolutely black, absolutely white, or ideally gray, so that, in accordance with Lambert's law, their radiation is assumed to be diffuse, i.e., with a brightness that does not depend on the direction of radiation. As a result, in accordance with the Stefan-Boltzmann law, the heat emitted from a surface unit is defined as:

\[ Q_n = \varepsilon \cdot \delta_0 \cdot T_n^4, \]

where \( \varepsilon \) is the degree of blackness of the surface; \( \delta_0 \) the Stefan-Boltzmann constant; Surface temperature. Correspondingly, the absorption and/or reflection of radiative heat by the surfaces participating in radiative heat exchange are modeled [5]. These equations were solved by the finite volume method.

For the process of distribution of the temperature field studied, the following boundary conditions were set: on the surface of the model, a boundary condition of the third kind is given.

\[ \lambda_n \frac{\partial T}{\partial n} = -\alpha_s (T - T_c) - \beta (T^4 - T_e^4) \]

Considering that the edge of the leg is a drain of thermal energy due to conductive connections with the "cold" environment, its temperature was set as a constant. (A boundary condition of the first kind \( T = T_e \)).

The necessary boundary conditions for modeling were set as follows:
1. The temperature of the "cold" edge of the investigated model \( T = 20^\circ C \).
2. The value of the electric current passing through the circular area of the heat-loss anemometer, with the following values: 1; 5; 10; 15; 20; 30; 40; 60; 80; 100; 120 mA.
3. Ambient temperature (air) \( t = \text{const} = 22^\circ C \).
4. The coefficient of thermal conductivity (at \( t = 300 \, ^\circ C \)) \( \lambda = 490 \, \text{W/m} \cdot \text{K} \);
5. Seebeck coefficient (at \( t = 300^\circ C \)) \( \alpha = 0.009 \, \text{W/K} \);
6. Electrical resistance of silicon carbide \( R = 0.01 \, \Omega \cdot \text{m} \).

Figure 2. Temperature field in the microsystem.

Qualitative analysis of the temperature field on the color images, the shape and nature of the distribution of isotherms in
the microsystem allowed us to identify the following features (see Fig.2). In the limit of the radiating site, the temperature field can be characterized as uniform. While in the area of the base of the structure there is clearly seen a strong unevenness in the distribution of temperatures. At the same time, the maximum temperatures in both cases differ significantly (374 °C in the first case and 427 °C in the second case). This is due to the presence in one of the models of a through hole, which prevents the free flow of heat flow, which, when encountering an obstacle, lingers on a circular platform. It should be emphasized that the temperature dependence of the SiC thermal conductivity, in particular its decrease with increasing temperature, plays an essential role in the processes considered [7].

According to the obtained data, curves for the dependence of the electric current on the temperature of the model under study at two points, the hottest point (1), and the coldest point (2) itself, shown in Fig. 3, are plotted. Figure 3 shows that the thermal model with a through hole is preferable, in consequence of the fact that the temperature of the thermo-anemometer in working condition has less effect on the thermometer located on the foot of the microsystem. In this case, the inverse thermal effect is excluded from the calculation, since the working temperature of the thermometer is assumed to be equal to the temperature of the medium being measured.

![Figure 3](image)

**Figure 3.** Graph of the temperature dependence of the microsystem at the "hot spot" itself on the magnitude of the electric current.

The obtained results can be regarded as a prerequisite for experiment on real prototypes.

**Conclusions**

In the course of the study, a method for calculating the micro-system was proposed, showing the mutual thermal effect of the elements.

According to the data of the study, curves for the dependence of the electric current on temperature are plotted, as shown in Fig. 3.

Based on the results of the simulation, it can be judged that the tested versions of the microsystem designs have significant temperature differences >50 °C in the presence of small design solutions.

**References**
1. Baicar R I, Varshava S S, Potapchyk G N and Chekyrin V F 1994 Pribori I tehnika eksperimenta Devices and experiment technique 3 pp 158-163

2. Karachinov V A 1995 Termoanemometer na osnove karbida kreminja Silicon carbide thermoanemometer Works of the international seminar «Semiconductor silicon carbide and devices based on it» Novgorod pp 72-73

3. Yanyushkin A S, Medvedeva O I, Saprykina N A 2014 Mechanism of Protective Membrane Formation on the Surface of Metal-Bonded Diamond Disks Applied Mechanics and Materials 682 pp 327-331

4. Saprykin A A, Ibragimov E A, Babakova E V 2016 Modeling the Temperature Fields of Copper Powder Melting in the Process of Selective Laser Melting IOP Conference Series: Materials Science and Engineering 142(1) 012061

5. Aljamovskijj A A, Sobachkin A A and Odincov E V 2005 Solid Works Komp'juternoe modelirovanie v inzhenernojj praktike[Computer simulation in engineering practice] SPb pp 799

6. Shlikhtin G 1974 Teoria pogranichnogo sloya Boundary layer theory Moscow Science pp 70-72

7. Lykov A V 1978 Teplomassoobmen: Spravochnik Heat and mass transfer: a directory Moscow Engineering pp 560