Multifunctional anemometric microsystem based on silicon carbide

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Abstract. The results of optical methods for diagnostics of hot gas flows from an image are presented, taking into account the features of TV diagnostics of hot gas flows. The design of the SiC - universal anemometric Microsystem (UAMS) was proposed and investigated, and mathematical and thermal models of the pendulum - Microsystem were presented. A series of calculations and simulations were performed to estimate the degree of influence of temperature, gas flow velocity, and spatial orientation of the probe on the temperature field in it. It is shown that according to the conducted research, the gas flow rate has a weak effect on the temperature distribution in the selected directions in the pendulum - Microsystem. For example, when the pendulum was longitudinally blown with air, the maximum temperature difference did not exceed 0.1 K. This indicates a high stability of the characteristics of the pendulum-SiC Microsystem.

1. Introduction
Methods for diagnosing incandescent gas flows (flames) are a scientific basis that is of considerable interest in the implementation of both fundamental and applied research of low-temperature plasma, combustion processes, gas flows at hypersonic speeds, as well as various technical systems - gas turbines, burners, heat exchangers, etc. etc. There are a number of electrical methods for measuring the temperature and velocity of heated gas flows using thermocouples, thermocouples, various anemometers, as well as optical methods using the flow's own radiation or an external source. [1-9].

The well-known advantages of optical methods are increased information content and performance, as well as the possibility of remote measurements in real time [10-16]. The well-known methods of thermal and laser anemometry [12-17] are most often used to measure the flow rate in a flame. At the same time, in the scientific literature, information on television methods for measuring the speed of an incandescent gas flow (flame) from an image is limited. Of particular interest, by analogy with probe pyrometry [4], are the methods of television anemometry using micromechanical systems adapted to the measurement technology [16].

2. Research methodology
Description of the microsystem design. Taking into account the peculiarities of television diagnostics of incandescent gas flows, the design of SiC, a universal anemometric microsystem (UAMS), built according to Wild's principle (figure 1), was proposed [16, 17].
The engineering basis for the design of this UAMS was based on and implemented the following defining criteria: diminutiveness; mechanical strength; thermal burning of the structure; contrast of the UAMS image; high emissive properties; manufacturability [7].

Figure 1. A variant of the design of the SiC-universal anemometric microsystem according to Wild's principle. a - image of the microsystem. Photo. ; b - structure (1 - rod-holder; 2 - fork holder; 3-axis; 4 - pendulum-emitter).

3. Measuring block diagram
The principle of measuring the velocity and temperature of a gas flame from the SiC - UAMS image is shown in figure 2. Using a gas system including a gas source (1) and a nozzle (2), a diffusion flame (3) is formed with a classical structure containing a core, a recovery zone and a torch. In the studies, the SiC-UAMS design was used, which consists of a fork holder (4) and a pendulum-emitter (5) in the form of a pyrometric probe with limited conductive coupling [17].

Figure 2. Block diagram of the measuring stand.

The input and movement of the UAMS in the flame was carried out using a positioner (6) with a U-shaped rod-holder according to a signal from a controller (7) connected to a PC (9). Under the action of the force of pressure (head) of the gas flow, the pendulum deviated from the vertical position by an angle proportional to the speed of the gas flow. By registering with a television pyrometer (8) the projection of the UAMS image and using digital methods of its processing, for example, using the Fakel
1.0 software [12], the angle of deflection of the pendulum from the vertically oriented fork holder was measured with the subsequent calculation of the flow velocity value (figure 3).

Figure 3. Principle of measuring the brightness temperature of the gas flow and the angle of deflection using SiC - UAMS. Example. A photo. Experiment. Software "Fakel 1.0".

4. Research results and their discussion. Modelling the thermal regime of a universal microsystem
Most of the SiC - pendulums, developed and studied in this work, are structurally presented in the form of lamellar structures of a simple shape. On the one hand, this simplifies the process of constructing their thermal models on the basis of already known ones, and on the other, it requires taking into account a number of specific points related to the analysis of their thermal regimes.

It is known that a characteristic feature of thin plates is a small temperature drop in the cross section, which in most cases can be considered equal to zero [6, 7]. In this case, the process of heat propagation in the plates differs significantly from the process of heat propagation in the walls: the heat flux flowing through any isothermal surface of the wall without internal heat sources in a steady state is unchanged. At the same time, heat flux of different magnitude passes through different isothermal surfaces of the plate. This is due to the fact that during the transfer of thermal energy by conduction in the plate, the processes of continuous absorption and dissipation of heat due to convection and thermal radiation occur simultaneously. It should also be emphasized that both the temperature Ti of the isothermal surface (i) and the heat flux flowing through it, are functions of the surface coordinates [6,7].

The characteristic features of the pendulum variants under consideration are:

- The design of the pendulum is a fairly thin plate (d ≤ 500 μm).
- A strong dependence of the numerical values of the thermal conductivity coefficient of SiC on temperature is observed (figure 4.14) [3,15].
- At temperatures above T≥500°C, there is no reliable information about the numerical values of the thermal conductivity coefficients of SiC: λx, λy, λz. [1,3,13,15].
- The technique of measuring the brightness temperature using a television pyrometer is carried out in the "freeze frame" mode (instant shooting) [13].

5. The shape of the pendulum's emitting area is a circle
Figure 4 shows the thermal model of the pendulum under the conditions of lateral and longitudinal blowing by an isothermal gas flow with temperature Tf and velocity V. The point of “sticking” (•) A is shown, in which the most intense washing of the pendulum by the incident flow is observed. The main mechanisms for heating the pendulum in the thermal model were considered forced convection and thermal radiation. In this case, the numerical values of the convection heat transfer coefficient 𝛼k were obtained from preliminary calculations using the well-known similarity method [5,6]. A number of computer experiments also took into account an insignificant
Heat flux removal through conductive connections of the pendulum with a fork holder by introducing corresponding ribs marked “heat drain”. The material of the pendulum (SiC) was considered isotropic, but the temperature dependence of the thermal conductivity coefficient was taken into account (figure 5).

### Figure 4
Thermal model of a pendulum with a circular emitting area under conditions of lateral (a) and longitudinal (b) airflow.

### Figure 5
Temperature dependence of the thermal conductivity coefficient of a single crystal of silicon carbide of the 6H polytype.

Within the framework of the mathematical model of the pendulum, a nonlinear problem of heat conduction was considered in the form of a system of the following equations:

**well-known general equation of heat conduction:**

\[
C_p \rho \frac{\partial T}{\partial t} = \lambda_x \frac{\partial^2 T}{\partial x^2} + \lambda_y \frac{\partial^2 T}{\partial y^2} + \lambda_z \frac{\partial^2 T}{\partial z^2} + q_0
\]  

(1)

**boundary conditions:**

- at the vertices of the models (label A) the condition of the first kind:
  
  \[T = T_f\]

  (2)

- a condition of the third kind was set at the outer boundaries of the models:

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

  (3)

Where: \(\beta\) - is a value equal to the product of the Stefan-Boltzmann constant \((\sigma_0 = 5.7 \times 10^{-8} \text{ W} / \text{m}^2\text{K}^4)\) by the emissivity of the surface of the probe material; \(\alpha_k\) is the convection heat transfer coefficient.

The system of equations (1-3) was solved by the finite element method using the ANSYS Workbench software with the following parameters of the geometric model of the pendulum: length 16 mm, width 3 mm, thickness 0.3 mm, hole size in the leg 0.5 mm, contact pad size 8 mm.

- stage-1: loading all previously prepared options into the computational analysis;
- stage-2: import of material data (SiC) used in models;
• stage-3: setting the boundary conditions and carrying out the calculation;
• stage-4: Visually evaluate the model and record the results.

A series of calculations was performed, which made it possible to solve the following series of problems: to assess the degree of influence of temperature, gas flow velocity, and also the spatial orientation of the probe on the temperature field in it.

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Figure 6. Temperature distribution in a pendulum with a round emitting area. a - lateral airflow; b - blowing from below. Calculation. Software "ANSYS", grid step δ = 0.2 mm. Example: air, V = 10 m / s; Tf = 1200°C.

Figure 6 shows examples of the results of computer simulation of the temperature field in a pendulum. The color contrast clearly shows that in both cases the emitting area of the pendulum is sufficiently isothermal, which guarantees reliable pyrometric measurements of the brightness temperature.

Figure 7. Influence of the gas flow rate on the temperature distribution in the selected directions of the pendulum. Longitudinal airflow. Payment. Example: air, Tf = 1000K. 1 - flow velocity V = 0.5m / s; 2 - flow velocity V = 50 m / s.

6. Conclusion
According to the studies carried out, the gas flow rate has a very weak effect on the temperature distribution over selected directions in the pendulum. So, for example, when the pendulum is blown longitudinally by air with a temperature of Tf = 1000 K and with velocities of ~ 0.5 m / s and ~ 50 m / s, the maximum temperature difference did not exceed 0.1 K (figure 7). This indicates a high stability of the characteristics of the SiC pendulum.
Reference
[1] Gordov A N 1962 Measurements of temperatures of gas streams (M.: Mashgiz) p 284
[2] Esterkin R I, Isserlin A S and Pevzner M I 1981 Thermal measurements during the combustion of gas and liquid fuels (L.: Nedra) p 200
[3] Gil V V 1984 Optical methods for studying combustion processes (Moscow: Nauka) p 169
[4] Karachinov V A, Karachinov D V and Toritsin S B 2006 Probe methods of television pyrometry of heated gas streams (NovGU named after Yaroslav the Wise Veliky Novgorod) p 108
[5] Seleznev B I, Karachinov D V, Karachinov V A and Toritsin S B 2006 The method of regular optical marks in pyrometry of heated gas flows Journal of Optical Technology 73(5) 69-70
[6] Aleseev M M and Samsonov V P 2007 Method of digital photometry in the study of the structure of a vortex dam Letters to ZhTF 33(11) 34-9
[7] Karachinov V A, Chelpanov V I, Ilyin S V and Karachinov D V 2011 The use of the lattice method for the study of heated gas streams Systems and communications for television and radio broadcasting 1-2 74-6
[8] Karachinov V A, Ilyin S V, Petrov A V, Manukhin V A and Ionov A S 2012 Lattice methods of visualization and investigation of the thermal structure of a diffusion flame Vestnik NovGU, ser. tech. science 68 95-7
[9] Manukhin V A, Karachinov V A and Karachinov D V 2014 Patent No.2528572 RF IPC G01P 5/10 Thermoanemometer and the method of heating its themoresistive structure No. 26
[10] Vasiliev L A 1968 Shadow methods (Moscow: Nauka) p 400
[11] Hauf V and Grigul U 1973 Optical methods in heat transfer (Moscow: Mir) p 240
[12] Poskachev A A and Chubarov E P 1988 Optoelectronic systems for measuring temperature (Moscow: Energoatomizdat) p 248
[13] Karachinov V A, Karachinov D V and Toritsin S B 2008 Investigation of the characteristics of a television pyrometer with a built-in temperature calibrator Measurement technology 7 42-5
[14] Karachinov V A, Karachinov D V and Ilyin S V 2012 Methods of television thermometry of heterogeneous systems LAP LAMBERT Academic Publishing 298
[15] Karachinov V A, Karachinov D V, Kazakova M V, Evstigneev V A and Bondarev D A 2017 Refractometric SIC-detector with a hole microrelief Bulletin of RGRTU 62 184-90
[16] Karachinov V A, Zverev K A, Evstigneev D A and Varshavsky A S 2018 Television method for measuring the characteristics of diffusion flame according to Wild's principle 15th International. conference "Television: transmission and processing of images" (Proceedings - St. Petersburg) p 99-102
[17] Yeh Y and Cammins H Z 1964 Localized fluid flou measurements with a He-Ne laserspectrometer Appl. Ph. Let. 4(10)