1. Introduction

It is known that thin, optically transparent plates made of semiconductor or dielectric materials quite often play the role of sensors in optical interferometry, refractometry and pyrometry. The listed methods are of traditional interest for solving problems associated with the registration of heat flow fields in the study of aerodynamic heating, gas discharges (plasma), combustion processes, as well as in the diagnosis of various technical systems. Depending on the temperature of the gas stream, the following methods are currently used: based on changing the optical path length in the detector material; on a change in the field of angles of deviation of the light beam in the material and the field of brightness temperatures [1–5]. For extreme conditions, single-crystal silicon carbide (SiC) is relevant as the base material of heat flux sensors. This chemical compound is known to be essentially diamond. In it, half of the carbon atoms are replaced by silicon atoms having less stable sp3 configurations. This feature creates great opportunities for combining communication functions and the formation of a large number of polytypes. Silicon carbide is a material with a natural layered structure at the nanoscale level. Competitive advantages of single-crystal silicon carbide are: optical transparency, the possibility of dyeing during alloying, high hardness, radiation, chemical and thermal resistance, and the ability to control properties through polytypism. The current industrial technology for growing large diameter silicon carbide ingots (> 50 mm) allows the creation of large-area refractometric detectors (visualizers) [6–9]. Therefore, in this work, we present the results of a study of the morphology of the temperature field when a diffusion flame flows around the surface of SiC detectors of this type.

2. Research methodology

Round-shaped test detectors with a diameter of 50 mm and a thickness of ~ 450 μm were made of a bulk ingot of semi-insulating silicon carbide of polytype 6H by wire cutting and subsequent double-sided polishing of (0001) C and (0001) Si faces using standard technology. The average height of surface irregularities according to the TALYSURFCCI-2000 optical measuring system was 0.12 μm. The
detector samples did not contain visible microdefects of the structure and had polytype uniformity. Modeling of the morphology of the temperature field of the detector was carried out by the method of field characteristics in the “COSMOSFloWorks” environment in a stationary setting [10].

Experimental studies were carried out in the temperature range 800 ÷ 1300 °C on a laboratory bench, which consisted of a gas nozzle system (propane), a two-coordinate positioner for immersing the detector in a flame, a reference heat receiver (TXA thermocouple (chromel-alumel) with a maximum permissible temperature \( T = 1300 \, ^\circ\text{C} \)). Thermo-EMF was measured using a digital voltmeter (MY-63). Studies were performed at various angles of attack of the incident gas flow and face of the detector. To obtain an image of the detector and measure its temperature, we used a television monochromatic pyrometer of luminance type (effective wavelength \( \lambda_e = 0.6 \ldots 0.72 \) and \( 1.5 \mu\text{m} \)) whose electronic control system of a matrix photodetector (FPSS) which made it possible to visualize surface areas of a SiC detector with different brightness temperature in the conditions of idle automatic gain control (AGC). The process of calibrating the pyrometer and measuring the surface temperature of the detector was carried out using a personal computer (the Parus – K program) [4].

3. Research results and discussion

3.1. Modeling. Physical model

A SiC detector in the form of a horizontally oriented smooth plate was considered as a nonlinear, gray, isotropic medium (figure 1). The temperature dependence of the emissivity and thermal conductivity of silicon carbide was taken into account [10, 11]. Hot air with a cylindrical torch was chosen as a model gas medium that exerts a thermal effect on the refractometric detector. The empirical dependences of the viscosity and thermal conductivity of these air components on temperature and density on pressure were used. The angle of inclination of the torch with respect to the plate was set the air was \( 1 \div 20 \, \text{m/s} \) and the temperature was \( 400 \div 1300\,\text{°C} \). Environmental conditions were chosen normal.

Figure 1. Physical model.
3.2. Mathematical model
In COSMOSFloWorks, the movement and heat transfer of heated air was modeled using the well-known Navier-Stokes equations, which describe the laws of conservation of mass, momentum and energy of this medium in a non-stationary setting:

\[
\frac{\partial \rho}{\partial t} + \frac{\partial \rho \cdot u_k}{\partial x_k} = 0 \tag{1}
\]

\[
\frac{\partial \rho \cdot u_k}{\partial t} + \frac{\partial \rho \cdot u_i \cdot u_k}{\partial x_i} - \tau_{ik} + \frac{\partial P}{\partial x_i} = S_i \tag{2}
\]

\[
\frac{\partial (\rho \cdot E)}{\partial t} + \frac{\partial \rho \cdot E + P}{\partial x_k} q_k - \tau_{ik} \cdot u_i = S_k \cdot u_k + Q_H \tag{3}
\]

where \( t \) - time, \( u \) - fluid velocity, \( \rho \) - fluid density, \( P \) - fluid pressure, \( S_i \) - external mass forces acting on a unit mass of a fluid: \( S_{\text{porous}} \) - porous body resistance action, \( S_{\text{gravity}} \) - gravity action, \( S_{\text{rotation}} \) - action of a rotating coordinate system, i.e., \( S_i = S_{\text{porous}} + S_{\text{gravity}} + S_{\text{rotation}} \); \( E \) - total energy of a single fluid mass, \( Q_H \) - heat generated by a heat source in a unit volume of fluid, \( \tau_{ik} \) - viscous shear stress tensor, \( q_i \) - diffusion heat flux, subscripts mean summation in three coordinate directions. In this case, the laminar and turbulent boundary layers of the air flow near the detector surfaces, as well as the transition of the laminar boundary layer to turbulent one and, on the contrary, are modeled using modified universal wall functions [10].

3.3. Simulation results
The calculations showed that, when the incident air flow interacts with the ideal smooth surface of the detector, a fairly symmetric thermal trace is formed on it with a characteristic morphology shown in figure 2. The temperature value of the central zone of the field most strongly depended on the temperature and speed of the incoming air flow. So, in the range of air velocities of \( 1 \div 10 \) m/s, a linear nature of the increase in this temperature was observed. And at a constant air flow rate, an increase in its temperature caused a monotonic increase in the temperature of the central zone. It should be noted that in the framework of computer simulation, the maximum values of the surface temperature of the detector always turned out to be 5-6 times lower than the temperature of the air flow. The noted features are due to the geometric and thermophysical properties of the SiC heterogeneous system [11, 12].
3.4. Experiment

The application of the field characteristics method in the framework of experimental studies made it possible to obtain quantitative characteristics of the thermal state of the SiC detector from its recorded pyrometric brightness contrast (image) (figure 3a). Image processing in the thermogram mode (figure 3b) taking into account the edge effects as a whole did not reveal a significant difference in the morphology of the temperature field obtained in the simulation. As a rule, a typical system of zones was visualized, symmetrically oriented relative to the axis of the torch. In this case, the central zone with maximum brightness (224 eu) also corresponded to the area of contact of the torch with the detector surface. Detailedization of the features of the temperature field by the selected contour method (figure 3c) showed satisfactory agreement with the pyrometric measurements (IR – pyrometer – Mastech MS6530) of temperatures at control points. It should be noted that at a maximum torch temperature of 1300 °C, the temperature of the detector surface in the central zone was only ~ 300 °C. One of the reasons for this difference is the partial transparency of the SiC detector and, as a consequence, the low emissivity [11–13].

**Figure 2.** Morphology of the temperature field of a SiC detector. Payment. Example: air temperature \( T = 1200 \, ^\circ \text{C} \), average speed 20 m / s, angle of attack 30 degrees. (a – thermogram of heated air; b – thermogram of the surface of the SiC detector; c - temperature slice along the selected circuit).
Figure 3. Experimental studies. Example: gas temperature $T = 1300 \, ^\circ C$, average speed 10 m/s, angle of attack 30 degrees. (a – television brightness contrast; b – thermogram of the surface of the SiC detector; c – temperature section along the selected contour; • – control points).

4. Conclusion
According to computer and field experiments on visualizing the morphology of the temperature field of a SiC refractometric detector, the interaction of a heated air stream with the surface of the detector causes the formation of a typical system of isothermal zones symmetrically oriented relative to the torch axis. In this case, the central zone with maximum brightness corresponded to the contact area of the torch with the surface of the SiC detector.

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