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Changes in the dynamic characteristics of heat flux sensors based on anisotropic thermoelements in shock tube experiments

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A change in the dynamic characteristics of sensors on anisotropic thermoelements made of a bismuth single crystal was discovered when measuring intense heat fluxes ($> 1\,\mathrm{MW/m^2}$) in experiments on shock tubes in the case of using air as a working gas. A noticeable increase in the response time to thermal influence, as well as distortion of the shape and amplitude of the electrical signal and the heat flux calculated from it, are caused by the formation in thermoelements of a near-surface defective layer $< 1\,\mu$m thick, which is not involved in the generation of thermopower. This may limit the conditions for applicability of the sensor in experiments on shock tubes and requires periodic calibration of the sensor against the reflected shock wave to monitor the condition of the working surface and the value of the volt-watt coefficient

Keywords: heat flux, shock tubes, sensors based on anisotropic thermoelements, bismuth.

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A sensor based on anisotropic thermoelements made from single-crystal bismuth [1] is a convenient instrument for measurement of unsteady heat fluxes in shock tube experiments. It offers a high sensitivity ($\sim 10\,\mathrm{mV/W}$), a short response time ($< 0.1\,\mu$s), and a wide dynamic range ($\sim 0.1-10\,\mathrm{MW/m^2}$). Current experience shows that the exposure to nitrogen and argon heated to ~ 5000 K behind a reflected shock wave with a duration up to $100\,\mu$s does not induce thermal breakdown of thermoelements and soldered joints and changes in the volt–watt coefficient and dynamic characteristics of a sensor [2,3]. It has been demonstrated in [4] that the single-crystal structure may be disrupted in a thin near-surface layer of an anisotropic thermoelement in the process of fabrication of sensors. This is manifested in the generation of an electrical signal inconsistent with the unsteady heat flux affecting a sensor and in a noticeable increase in the time of response to thermal influence. The reason behind this is the formation of a defect layer that is not involved in the generation of thermopower. It is demonstrated in the present study that a similar disturbance accompanied by a change in sensor characteristics may also occur in measurements of intense heat fluxes ($> 1\,\mathrm{MW/m^2}$) with a duration up to 1 ms when air serves as a working gas.

The used heat flux sensor contained a single thermoelement 4 mm in length, 0.5 mm in width, and 0.35 mm in thickness. It was calibrated against a reflected shock wave [5] prior to the main series of measurements. A flange with the heat flux and pressure sensor, which was used to determine the exact moment of reflection of an incident shock wave, was mounted at the end of a driven section of a shock tube. The initial nitrogen pressure in the driven section was $p_1 = 50$ Torr, and the Mach number of incident shock wave was $\mathrm{M}_1 = 2.2$. An intermediate amplifier based on an INA128 instrumentation amplifier with a gain of x500 and an *RC* low-pass filter with a time constant of $5\,\mu$s was used to raise the signal-to-noise ratio in measurements at the lower range limit of an oscilloscope. This filter exerted a negative effect on dynamic characteristics of the sensor–amplifier system and reduced the working time, but also reduced the noise level considerably and raised the accuracy of measurement results. Sensor signals were registered a Tektronix TDS 2024C oscilloscope with a time step of $4 \cdot 10^{-8}$ s. Curves *3* and *1* in Fig. 1, *a* represent signals of the pressure sensor and the heat flux sensor, respectively. Oscillations of the pressure sensor signal have no relation to gas dynamics and are attributable solely to the transfer of mechanical vibrations via the contact of the flange at the tube end and the metal body. The horizontal line in Fig. 1, *b* is theoretical value $q_5\sqrt{t} = 2100\,\mathrm{W \cdot s^{1/2}/m^2}$ of the normalized heat flux behind the reflected shock wave calculated for the initial conditions of the experiment, while curve *1* corresponds to the flux calculated based on the sensor signal. The obtained volt–watt coefficient was $S_0 = 11\,\mathrm{mV/W}$. Curves *2* In Figs. 1, *a* and *b* represent the electrical signal and the normalized heat flux, respectively, in repeat calibration after two measurements from the main series. The working gas was air, and the sensor was mounted in front of a cylindrical obstacle at a distance of 0.5 mm from it. The average heat flux value in this case was $\sim 4\,\mathrm{MW/m^2}$ at an overall heating duration of ~ 1 ms.

In the main series of experiments, the heat flux was measured in the front separation region in supersonic air flow around a cylindrical obstacle. The formation of an extended region with horseshoe vortex structures within it

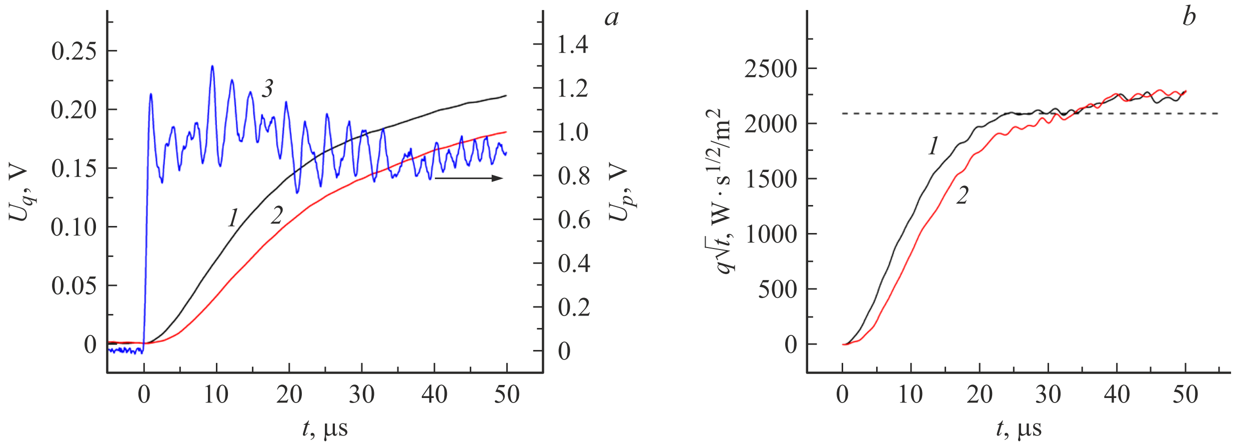

Figure 1. Electrical sensor signal (*a*) and reduced heat flux (*b*) with calibration against a reflected shock wave prior to measurements in air (*1*) and after measurements (*2*). *3* — Pressure sensor signal.

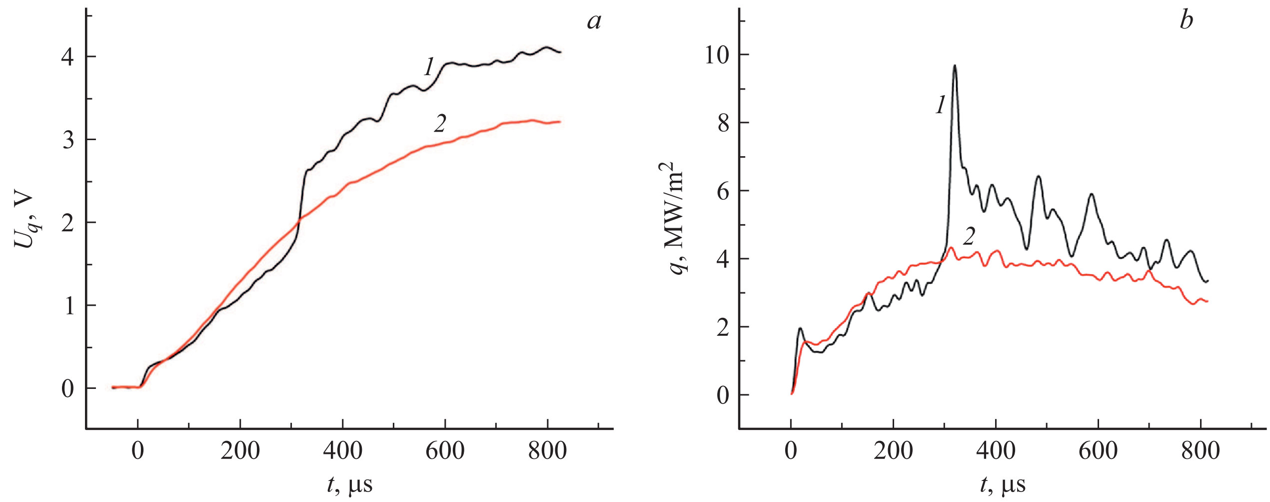

Figure 2. Electrical signal of the sensor (*a*) and heat flux (*b*) in the first (*1*) and repeat (*2*) measurements of the heat flux in the separation region in front of a cylinder.

is a specific feature of the gas-dynamic structure of flows of this type. This leads to a more than tenfold rise of the heat flux (relative to an unperturbed boundary layer [6]). Experiments were performed at a rectangular shock tube at the Ioffe Institute with a channel 50×150 mm in size. A cylinder 12 mm in diameter was mounted inside the driven section horizontally with its side surface facing the incident flow. The heat flux sensor was mounted flush with the inner tube surface in front of the cylinder at different distances from it and connected via an intermediate amplifier based on an INA128 instrumentation amplifier with a gain of x200 and no additional filter. To increase the spatial resolution, the anisotropic thermoelement was positioned with its short side facing the flow. Its electrical signal was registered a Tektronix TDS 2014 oscilloscope with a time resolution of $4 \cdot 10^{-7}$ s. Measurement data were processed in accordance with the procedure outlined in [7]. The initial air pressure in the driven section was $p_1 = 10$ Torr, and the Mach number of incident shock wave was $M_1 = 4.8$. The following parameter values were calculated for the initial conditions of the experiment: flow velocity behind the shock wave $V_2 = 1350$ m/s; density $\rho_2 = 0.087$ kg/m^3, temperature $T_2 = 1465$ K, and Mach number $M_2 = 1.8$; the Reynolds number calculated based on the cylinder diameter is $Re_2 = 2.5 \cdot 10^4$.

Figure 2 shows the electrical signal from the sensor mounted at a distance of 0.5 mm from the cylindrical obstacle (in the region of maximum heat flux values) and the corresponding calculated heat flux. Curve *1* represents the results of the first measurement performed when the sensor had no defect layer on the working surface. Owing to the unsteady nature of flow, heat flux oscillations have a large amplitude (~ 1 MW/m^2) and a fairly high frequency (~ 10 kHz). Curve *2* corresponds to the results of a test experiment carried out after several measurements at various distances from the cylinder. The electrical signal

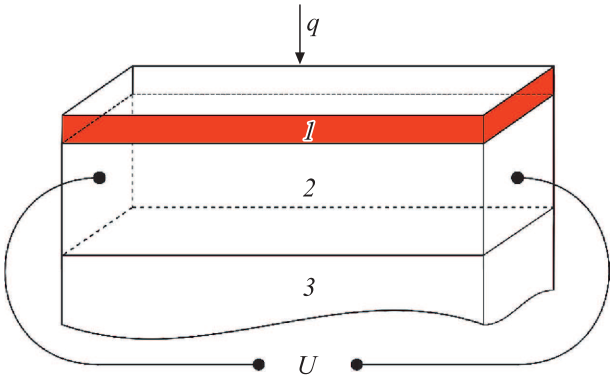

Figure 3. Structure of the heat flux sensor. *1* — Defect layer with a disturbed single-crystal bismuth structure, *2* — undisturbed part of the anisotropic thermoelement, *3* — model surface.

is evidently smoothed in this case, and high-frequency pulsations in the heat flux curve are lacking, indicating the emergence of a defect layer on the working surface of anisotropic thermoelements. The closeness of average values of the heat flux suggests that the volt–watt coefficient of the sensor did not change in any significant way after measurements.

A similar pattern is observed in repeat calibration, which was performed right after the measurement of intense heat fluxes (curves *2* in Fig. 1). The response time increased markedly, while the signal amplitude decreased relative to those corresponding to calibration of a newly made sensor without a defect layer. The reduced heat flux curve calculated based on the sensor signal became smoother and lacks a section representing the phase of steady-state heat exchange. Numerical calculations, which were similar to those performed in [4], revealed that this increase in the time of response to pulsed heating correspond to a defect layer thickness $< 1\,\mu$m. It should be noted that this dynamic performance degradation is naturally more apparent in measurements with a short characteristic time (e.g., in calibration against a reflected shock wave).

The obtained experimental data revealed the influence of heat flux density on the variation of dynamic characteristics of the sensor. Multiple measurements at large distances from the cylindrical obstacle, where the heat flux is comparable to its value in an unperturbed turbulent boundary layer ($\sim 500\,\text{kW/m}^2$), did not lead to deterioration of the dynamic performance, indicating that the defect layer had a negligible (or zero) thickness. At the same time, multiple experiments at small distances, where the heat flux is maximized and reaches a level of $\sim 10\,\text{MW/m}^2$, induced gradual deterioration of the dynamic performance of the sensor and, consequently, an increase in thickness of the defect layer. When the working surface of anisotropic thermoelements was sanded with P2500 paper with intermediate calibrations, the sensor restored gradually its initial dynamic parameters, indicating that the defect layer thickness decreased. It should be understood that the thickness of anisotropic thermoelements decreases in the process; these changes need to be taken into account in calculations of the heat flux. In experiments with the maximum heat impact, the temperature of the working surface of anisotropic thermoelements did not exceed 320 K, which is well below the melting point of bismuth (544 K). Owing to the presence of numerous uncontrolled influencing factors, it is rather hard in the present case to determine the mechanism of perturbation of the single-crystal structure of bismuth without a detailed analysis.

In the one-dimensional approximation and under the condition that thermopower is generated within the entire volume of the sensor based on anisotropic thermoelements, its electrical signal is proportional to the ratio between the difference of temperatures at its working and back surfaces and the sensor thickness: $U(t) \sim (T_h - T_0)S_0/h$, where S_0 is the volt–watt coefficient [2]. The transformation of single-crystal bismuth in a thin near-surface layer of the thermoelement into a structure taking no part in the generation of thermopower transfers the upper boundary of the generation region deeper into the thermoelement (Fig. 3) and reduces thickness h. The presence of such a layer with a significant thermal resistance induces an increase in the time of response to thermal influence and a suppression of temperature gradients near the upper boundary of the generation region. This results in distortion of the calculated heat flux, which deviates considerably from the one acting on the working sensor surface.

The obtained experimental data demonstrated that a defect layer with thickness $< 1\,\mu$m, which is not involved in the generation of thermopower, may form near the working surface of anisotropic thermoelements made from single-crystal bismuth in the process of measurement of intense heat fluxes ($> 1\,\text{MW/m}^2$) in shock tubes in air. This has a negative effect on the dynamic performance of a sensor and makes it impossible to record high-frequency components of the heat flux. A sensor needs to be calibrated periodically against a reflected shock wave to monitor the state of its working surface. The sensor thickness may decrease considerably in multiple repeat measurements accompanied by the formation of a defect layer and its periodic removal by polishing of the working surface. Periodic calibration against a reflected shock wave and correction of the volt–watt coefficient are needed to make a proper allowance for this variation of thickness.

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Conflict of interest

The authors declare that they have no conflict of interest.

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