The analysis of applicability of thermoelectric radiation detectors for heat flux measurements behind a reflected shock wave

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Abstract. The study is devoted to assessing the applicability of the manufactured thermoelectric sensor to measure pulsed heat fluxes in shock-wave processes. It is shown that the created thermoelectric sensor has fast response time and sufficient level of electric signal and can be successfully used in short duration high speed gas dynamic experiments.

1. Introduction

Pulsed gas-dynamic facilities, in particular shock tubes, are effective tools for creation and investigation of high-speed gas flows. Serious requirements are imposed to the diagnostic tools used for studying supersonic flows in terms of minimum dimensions, mechanical and thermal strength, sensitivity and noise immunity. Also, the sensors must have a short response time, since the maximum test time of these facilities does not exceed a few milliseconds.

Measurements of surface temperature and heat flux are very important part of complex research of interaction between high speed flows and solid surfaces. The main feature of these measurements is the short characteristic times of the investigated processes and high thermal and mechanical loads affecting to the sensor surface. For these purposes, different types of sensors have been successfully used for a long time - thin-film sensor [1, 2], coaxial surface junction thermocouple (CSJT) [3-5], thin-wire thermocouple [6], atomic layer thermopile (ALTP) [7], gradient heat flux sensor (GHFS) [8-11].

Authors has developed and manufactured thermoelectric heat flux sensors based on the artificially anisotropic film obtained by vacuum deposition. These sensors are successfully used in laser systems for measuring the radiation power [12, 13]. The main distinguishing feature of thin-film thermoelectric
sensors is the ability to calculate the heat flux density directly from an electrical signal. The work is devoted to the study of the applicability of sensors in a gas-dynamic experiment on shock tubes. The measurement of the heat flux during the shock wave reflection from the end of the shock tube was chosen as a test problem. This choice is due to the good reproducibility of the gas parameters behind the reflected shock wave, the possibility of varying these parameters in a fairly wide range, and the short characteristic times (~ 1 µs) of thermal processes during shock reflection.

2. Sensor description

The team of the Institute on Laser and Information Technologies (ILIT) RAS has rich experience in the manufacture and implementation of thermoelectric detector mirrors with thermal electromotive force (emf) anisotropy which were originally designed as laser radiation detectors [12]. The performance of these sensors is based on the generation of thermal emf in the direction perpendicular to the temperature gradient in the sensitive element with anisotropy of the thermoelectric coefficient [14, 15]. The sensitive element of the device is an anisotropic film created by the oblique angle thin film deposition technique. This sensitive element contains two layers (Figure 1a). Its base is a 0.4 mm thick layer of high-resistance silicon, thermo-oxidized on both sides. On the front side of this layer, a structure of anisotropic chromium layer with a thickness of 0.3 µm is applied with contact areas above it for registering thermal emf. By thermal evaporation in vacuum at a condensation angle of 60-80 degrees, an oblique anisotropic chromium-based film with a thickness of 0.3 microns is applied. In this case, chromium is built on the substrate in the form of a columnar structure, inclined at 60-50 degrees. The thermoelectric heat flux sensors fabricated in-house in the above process are shown in figure 1b.

![Diagram](image1.png)

**Figure 1.** (a) Scheme of thermoelectric heat flux based on artificially anisotropic thin films; (b) photograph of the fabricated sensors.

3. Experimental setup

The experiments were carried out using a shock tube at the Ioffe Institute (figure 2a) [16]. Driver tube has a length of 1.0 m, driven tube is of 4.3 m, an inner diameter is of 50 mm. The incident shock wave velocity was measured using piezoelectric pressure transducers mounted flush to the inner surface of the driven tube at a distance of 58 mm from each other. The pressure transducer signals were recorded with a digital oscilloscope Tektronix TDS 2024C with a step of 0.2 µs. Shock velocity was calculated by measured time interval of the shock wave passing the distance between the pressure transducers. Further, the parameters of the gas behind the incident and reflected shock wave were determined from the known Mach number and initial pressure in the driven tube.
To study the response of a thin-film thermoelectric sensor based on artificial anisotropy to pulsed thermal processes, it is necessary to measure its signal during a process with a known heat flux. For this purpose, simultaneous heat flux measurements were carried out using a thin-film thermoelectric sensor and gradient heat flux sensor (GHFS). GHFS based on bismuth anisotropic thermoelements have a short response time to pulsed thermal loads of \(~10\) ns [8] and have demonstrated good performance in shock tube experiments [9]. Since thermoelements of the GHFS have a thickness of about 0.1 mm, then for heat flux measuring with characteristic times less than 10 ms, mathematical signal processing is required. The temperature distribution in the two-layer thermoelement-substrate structure was calculated using the nonstationary one-dimensional heat equation with boundary condition relating the variation of sensor’s working surface temperature \(T_h(t)\) with the electric signal \(U(t)\) recorded in the experiment. The heat flux through the sensor working surface \(q_h(t)\) was calculated using the known temperature distribution \(T(x, t)\) [17].

To perform simultaneous heat flux measurements, a thin-film thermoelectric sensor, the GHFS, and a piezoelectric pressure transducer D3 were installed on a flange at the end of the driven tube (Figure 2b). A flange was made of non-conductive material (textolite). Pressure transducer D3 was used for synchronization of measurements. The heat sensors were insulated laterally and deeply from the flange body with the epoxy layer. To provide additional heat dissipation, an aluminum plate with dimensions of 8x5x3 mm was placed under the H2 sensor. This design allowed the thin-film thermoelectric sensor to hold out high mechanical and thermal loads under conditions of high intensity shock wave reflection.

Three series of experiments with varying driver and driven gas pressures were carried out, and, accordingly, the parameters behind the incident and reflected shock and the magnitude of the heat flux were changed. Nitrogen was used as a driver and driven gas. Table 1 shows the gas pressure and temperature behind the reflected shock wave. The calculations were made according to the ideal theory [18], which can be used at low Mach numbers \(M<5\) while the nitrogen dissociation is negligible.

| Mach number | \(P_1, \text{kPa}\) | \(P_4, \text{kPa}\) | \(P_5, \text{kPa}\) | \(T_5, \text{K}\) |
|-------------|------------------|------------------|------------------|------------------|
| 3.06        | 3.72             | 2940             | 202              | 1319             |
| 3.14        | 1.67             | 2550             | 123              | 1427             |
| 3.19        | 0.78             | 1280             | 48               | 1406             |

Figure 3a shows a comparison of GHFS (H1) and anisotropic thin-film heat sensor (H2) for gasdynamic regime \(M = 3.06\) from the Table 1. The heat flux calculated using GHFS signals is shown in blue (H1). The signal of the H2 sensor is shown in red. The H2 signals was recorded directly without any amplification and did not require any post-processing. The shapes of GHFS and H2
signals are in good agreement which allows us to make the conclusion that H2 sensor signal is proportional to heat flux. Comparison of heat fluxes calculated using GHFS and H2 sensor signals was made for three regimes from Table 1. Figure 3b shows the dependence of H2 sensor signal magnitude from heat flux magnitude calculated using GHFS signals. This dependence makes it possible to determine the volt-watt ratio of the H2 sensor. For the examined conditions it is approximately (7.5±0.8)x10^{-4} V/W.

![Figure 3a](image1.png)  ![Figure 3b](image2.png)

**Figure 3.** (a) Comparison of heat flux calculated from the GHFS signals (H1) with the thermoelectric heat flux sensor signal (H2) in experiment with M = 3.06, P=2060 kPa; (b) Dependence of H2 sensor signal magnitude from heat flux magnitude calculated using GHFS signals

The next series of experiments was carried out using the xenon as driven gas. Since xenon has a high molar mass, the speed of sound in xenon is approximately 2 times lower than in nitrogen, which makes it possible to create shock waves of much higher intensity than in nitrogen, at comparable pressures in the driver and driven sections. Helium and hydrogen were used as driver gases. Under these conditions, temperatures behind the reflected shock wave are of the order of 7,000 - 10,000 K. In this case contribution of the radiative heat flux to the total heat flux is significant. Table 2 shows the parameters behind the incident and the reflected shock waves for the series of experiments in xenon.

| Mach number | P_1, kPa | P_4, kPa | P_5, kPa | T_5, K |
|-------------|---------|---------|---------|-------|
| 6.04        | 4       | 1280 (He)| 965     | 7600  |
| 7.02        | 4       | 2550 (H_2)| 1295    | 9050  |
| 8.64        | 2       | 1280 (H_2)| 982     | 10300 |

Figure 4 shows the results of the heat flux measurements during shock wave reflection with different Mach numbers in xenon using a thin-film thermoelectric sensor based on artificial anisotropy. It can be seen that the maximum values of the heat flux are significantly higher than in nitrogen and increase with an increase in the Mach number of the incident shock wave. The negative values of the heat flux, which are noticeable for the mode M = 8.64, correspond to the penetration of shock-heated gas radiation into the thickness of the sensor and noticeable heating of the substrate, therefore the temperature gradients could be inverted. In these cases, the direct heat flux calculation based on the sensor signal is incorrect and more detailed analysis of the temperature distribution in the "substrate - sensor" system is required.
Figure 4. Heat flux measurements conducted by thin-film thermoelectric sensor based on artificial anisotropy in different experimental conditions.

After the end of the series of experiments on measuring the heat flux during shock wave reflection in xenon, it was decided to open the driven section of shock tube to check out the condition of the end flange and the sensors installed on it. It turned out that the inner surface of the end flange and the working surface of the sensor are covered with a layer of soot. Apparently, the reason for the pollution was the thermal destruction of the textolite. Another experiment was carried out to assess the effect of such contamination on the sensor performance. The heat flux was measured during the reflection of the shock wave in nitrogen, the experimental conditions were repeated the regime 2 (M = 3.14) from table 1. Comparison of measurement results using a contaminated and un-contaminated sensor are shown at figure 5. It can be seen that, despite some changes, the pattern of the sensor signal remained unchanged - a sharp rise to the maximum value, then a gradual decline for tens of microseconds. The soot layer acts as additional thermal resistance in this case. It was shown at [10] that the presence of “defective” layer on the thermoelement surface increases the smoothness of its signal, which corresponds to results at figure 5.

Figure 5. Comparison of heat flux measured by uncontaminated sensor (blue line) and contaminated sensor (red line). Incident shock wave Mach number M = 3.14, pressure behind reflected shock wave $P_5 = 123$ kPa, temperature behind reflected shock wave $T_5 = 1427$ K.

4. Conclusion
Thermoelectric heat flux detectors based on artificially anisotropic thin films have been regarded for their usage in measuring heat fluxes in short duration shock tube flows. Heat flux measurements behind reflected shock wave in nitrogen and xenon were carried out. It has been established that the thermoelectric sensor based on anisotropic films has a short response time, a high level of the
electrical signal, and also sufficient mechanical strength under intense force and thermal influences. The results obtained demonstrate its applicability for thermal measurements in pulsed gas-dynamic experiments with a characteristic duration of 0.5-10 μs and in wide range of characteristic heat flux magnitudes (0.1-25 MW/m²).

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