Heat flux measurement at the initial phase of normal shock wave reflection using the sensor on anisotropic thermoelements

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Abstract. Thermal measurements were carried out using the sensors on anisotropic thermoelements during normal shock wave reflection with Mach number $M = 3 \ldots 5$. The method of processing of sensor’s electric signal has been tested at low signal / noise ratio and characteristic time $\sim 0.1 \mu s$.

1. Introduction
Near the surface of supersonic aircrafts a complex system of shock waves is formed. Under abnormal flight conditions, this can lead to a significant increase of the heat flux to the surface of the aircraft and its further overheating and destruction. The study of peculiarities of heat transfer and the possibility of supersonic flow structure controlling near the aircraft surface under various flight conditions remains one of the most important tasks of experimental gas dynamics [1–9].

Nowadays, experimental studies of interaction of high-enthalpy gas flow with models are mainly carried out at impulse facilities with working time $\sim 1 \ldots 10$ ms [10, 11]. Short working time of facilities imposes special requirements to the heat flux measurement technique. Sensors should have high mechanical strength, response time $\sim 1 \mu s$, large dynamic range and high noise immunity, including in conditions of strong electromagnetic fields. One of the sensors that fully satisfy these requirements is the thermal sensor based on anisotropic thermoelements, developed at the St. Petersburg Polytechnic University [12]. The sensitive element of the sensor consists of a battery of anisotropic thermoelements from a bismuth crystal $0.2$ mm thickness and $2 \div 10$ mm mm length connected in series. The dimensions in plan of thermoelements battery can vary from $2 \times 2$ mm to $10 \times 10$ mm, depending on the required sensitivity and geometry of the test model. The working principle of sensor is based on the Seebeck effect – generation of thermal emf in the direction perpendicular to the temperature gradient in the sensitive element with anisotropy of the thermoelectric coefficient [13]. These sensors have practically no thermal inertia, since electrical signal is proportional to the temperature gradient. At the experiment [14], the response time was obtained $\sim 10$ ns. Our experience shows that sensors on anisotropic thermoelements are a unique tool for heat flux measurements in complex conditions [15–17]. In [18] the method for heat flux calculation by sensor’s electric signal was proposed. It was tested on several simulation cases typical for shock tubes experiments with characteristic time $\sim 0.1 \ldots 1$ ms. In the present paper, the method
was used to process the sensor’s electrical signal registered during shock wave reflection. In this case, the characteristic process time is $\sim 0.1 \, \mu s$.

The main objective of the study was to analyze the method applicability in case of short duration and value of heat flux, as well as a low signal / noise ratio in experiments at shock tube. Therefore, we analyze reflection of shock waves with small Mach numbers.

2. Experimental setup

The experiments were carried out on a shock tube at the Ioffe Institute (figure 1a). The high-pressure chamber is 0.8 m length and low-pressure channel is 2 m length. Inner diameter of shock tube is 36 mm. Atmospheric air was used as the working gas.

Velocity of the incident shock wave was measured using piezoelectric pressure sensors $D1$ and $D2$ mounted flush with the inner surface of the low pressure channel at a distance of 200 mm from each other. The sensors' electrical signals were recorded with a Tektronix TDS-3014 digital oscilloscope with a discretization time $\Delta t = 0.4 \, \mu s$. The shock wave velocity was calculated from the measured time when shock wave travels the distance between sensors with an error $\approx 0.5\%$. Further, using the known Mach number, parameters behind the incident and reflected shock waves were determined.

Figure 1. Scheme of the experimental facility (a) and the appearance of the plug (b). (1) and (2) – high and low–pressure channel, (3) – diaphragm block, $D1$ – $D3$ – pressure sensors, $H$ – thermal sensor on anisotropic thermoelements.

A plug of non-conductive material was installed at the end of the low–pressure channel. On the working surface of plug the pressure sensor $D3$ and the thermal sensor on anisotropic thermoelements $H$ were located (figure 1b). The dimensions of the heat sensor in the plan were $10 \times 10 \, mm$, the thickness and height of the thermocouples is $0.2 \, mm$, the stationary calibration coefficient is $k = 14.4 \, mV/\text{W}$. The working surface of the pressure sensor was placed $2 \, mm$ upstream, which allowed to start the registration system to be started before the shock wave reflected from the surface of the heat sensor. The working surface of the pressure sensor stuck out $2 \, mm$ towards the flow, which allowed to start the registration system before the shock wave reflected from the surface of the heat sensor.

Electrical signals were recorded with a Tektronix TDS-1002 digital oscilloscope with discretization time $\Delta t = 1 \, ns$. Two series of experiments were carried out with similar initial conditions, but with different maximum recording time $t_{max} = 2.5 \, \mu s$ and $t_{max} = 10 \, \mu s$. This made it possible to register the heat flux at the initial phase of reflection and the further phase of cooling hot gas behind the reflected shock wave.

| Mach number of the incident shock wave | Parameters behind the incident shock wave | Parameters behind the reflected shock wave |
|--------------------------------------|------------------------------------------|-----------------------------------------|
|                                      | $P_2, kPa$ | $T_2, K$ | $\rho_2, kg/m^3$ | $P_5, kPa$ | $T_5, K$ | $\rho_5, kg/m^3$ |
| 2.98                                 | 20.5       | 763      | 0.09          | 101        | 1278     | 0.27          |
| 4.05                                 | 38.4       | 1152     | 0.11          | 236        | 2063     | 0.39          |
| 4.98                                 | 58.7       | 1561     | 0.13          | 404        | 2895     | 0.47          |
The Mach number of the incident shock wave was varied by changing the pressure in the high-pressure channel. In each experiment, the pressure in the low-pressure channel was 2 kPa. Sets of 1, 2, and 3 lavsan diaphragms with 0.01 mm thickness and sets of 1 and 2 diaphragms 0.08 mm thickness were used. This made it possible to change the Mach numbers of the incident shock wave in the range $M = 3 \ldots 5$. At lower values, the noise level was comparable with the sensor signal, which did not allow reliable processing of the experimental results. Table 1 shows the parameters behind the incident and reflected shock waves for some experiments. The parameters were calculated according to an ideal theory, which is permissible for small Mach numbers.

3. Experimental results

Figure 2a shows the registered electrical signal of the heat sensor and prepared for heat flux calculation. It is seen that before the reflection of shock wave, the average value remains almost unchanged. This suggests that heating of the sensor’s working surface due to radiation from the front of the shock wave under these conditions is negligible. At the moment of reflection, the monotonic growth of the sensor signal begins. It is seen that in the electrical signal there is high-frequency noise with a characteristic time $\sim 40 \text{ ns}$. Since it is present during all registration time, this suggests that the noise is not caused by gas-dynamic processes. Noise can be caused solely by peculiarities of the registration system. In the case with Mach number $M = 2.98$ of incident shock wave, the noise level of the electric signal reaches 50%. Such a low signal / noise ratio requires special preparation for calculating the heat flux. This case and the corresponding sensor signal can be considered as the lower boundary of the registrable heat fluxes in shock tubes experiments.

![Registered signal of thermal sensor and prepared for calculating the heat flux](image1)

![Calculated change of the sensor's working surface temperature](image2)

**Figure 2.** Registered signal of thermal sensor and prepared for calculating the heat flux (a) for different Mach numbers, and calculated changing of the sensor’s working surface temperature (b). Processing of sensor’s electrical signal was carried out according to the method proposed in [13]. The temperature distribution in the two-layer structure thermo-element-substrate was calculated on the basis of the one-dimensional unsteady heat transfer equation in iteration cycle:

$$C \rho \frac{dT}{dt} = \frac{\partial}{\partial x} \left( \lambda \frac{dT}{dx} \right)$$

with boundary condition relating the change of sensor’s working surface temperature $T_h(t)$ with the electric signal $U(t)$ recorded in the experiment:

$$T^{i+1}_h(t) = \frac{h}{k\lambda nlw} U(t) + T^i_0(t)$$

where $C$, $\rho$, $\lambda$ – heat capacity, density and heat conductivity, $T_h, T_0$ – temperature of the working and back surface of the thermoelements, $k$ – stationary calibration coefficient of the sensor, $n$ – number of thermoelements in sensor, $h, l, w$ – thickness, length and width of the thermoelements, $i$ – iteration.
counter. Then, using the known temperature distribution, the heat flux through the working surface of the sensor \(q_h(t)\) was calculated.

Figure 2b shows the calculated temperature changing of the sensor working surface \(T_h\) during the reflection of a shock wave with different Mach numbers. It can be seen that the heating does not exceed 0.25 K, therefore, the temperature change of the back surface of thermoelements is negligible. For this reason, only single iteration was sufficient to calculate the heat flux from the sensor signal.

Figure 3 shows the heat flux calculated by electrical signal during reflection of a shock wave with different Mach numbers for two time ranges. Figure 3a shows the initial phase reflection and the formation of the reflected shock wave. Figure 3b shows the heat transfer process from hot gas behind the outgoing reflected wave to the sensor’s cold working surface. It can be seen that at the initial phase, the heat flux increases rapidly and reaches its maximum value, then it begins to gradually decrease, which is caused by gas cooling near the wall. Due to the high thermal inertia of the thermoelements material \(e = \sqrt{Cp\lambda} \approx 3000\), heating of its working surface is negligible (figure 2b).

Calculated heat fluxes are in qualitative and quantitative agreement with the calculation results given in [19]. The general behavior of the curves coincides, the moment of reaching the maximum value and its value are in agreement with the results of numerical simulation.

![Figure 3](image_url)

Figure 3. The calculated heat flux through at the initial phase of shock wave reflection with different Mach numbers (a) and the subsequent phase of gas cooling near the wall (b).

4. Conclusion
The paper presents the results of thermal measurements using the sensor on anisotropic thermoelements in experiments with reflection of a shock wave with different Mach numbers. Two phases of the process are considered: the formation of a reflected shock wave and the heat transfer from hot near-wall gas layer to a cold sensor surface. The method for processing the electrical signal of the sensor has been tested at shock tube experiments with a characteristic time \(\sim 0.1 \mu s\). The applicability limits of the sensor on anisotropic thermoelements for recording pulsed heat fluxes at a low signal-to-noise ratio are determined.

Acknowledgement
The coauthors Kotov M.A. and Monakhov N.A. thanks for support the grant of President of RF (#MK-144.2020.1).

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