St. Petersburg Polytechnic University Journal. Physics and Mathematics. 2023. Vol. 16. No. 1.1
Научно-технические ведомости СПбГПУ. Физико-математические науки. 16 (1.1) 2023

Conference materials
UDC 533.6.071.3
DOI: https://doi.org/10.18721/JPM.161.177

Heat flux measurements of high speed flow around an axisymmetric body using sensors based on anisotropic thermoelements

N.A. Monakhov [1]✉, V.A. Sakharov [1], P.A. Popov [1]

[1] Ioffe Institute, Saint-Petersburg, Russia

✉ nikolay.monakhov@mail.ioffe.ru

Abstract. The study is devoted to measurements of heat flux with an external high speed gas flow around the axisymmetric model. Sensors based on bismuth anisotropic thermoelements were used. Experiments were carried out using Big Shock Tube. The models used for experiments were the combinations of a cone with an opening angle of 60 degrees and a cylinder. The models with heat flux sensors were placed in the outer section of the flat supersonic nozzle. The results were compared with theoretical estimates made using the effective length method. The data obtained demonstrate the applicability of sensors in gas-dynamic experiments with test times about 1 ms.

Keywords: heat flux, shock tube, high speed flow, heat flux sensor based on anisotropic thermoelements, gradient heat flux sensor

Citation: Monakhov N.A., Sakharov V.A., Popov P.A., Heat flux measurements of high speed flow around an axisymmetric body using sensors based on anisotropic thermoelements. St. Petersburg State Polytechnical University Journal. Physics and Mathematics. 16 (1.1) (2023) 450–455. DOI: https://doi.org/10.18721/JPM.161.177

Материалы конференции
УДК 533.6.071.3
DOI: https://doi.org/10.18721/JPM.161.177

Измерение теплового потока при высокоскоростном обтекании осесимметричного тела с помощью датчиков на анизотропных термоэлементах

Н.А. Монахов [1]✉, В.А. Сахаров [1], П.А. Попов [1]

[1] Физико-технический институт им. А.Ф. Иоффе РАН, Санкт-Петербург, Россия

✉ nikolay.monakhov@mail.ioffe.ru

Аннотация. Представлены результаты измерения теплового потока с помощью датчиков на анизотропных термоэлементах при внешнем обтекании модели высокоскоростным потоком аргона. Эксперименты выполнены на большой ударной трубе ФТИ им. Иоффе. Обтекаемые модели представляли собой комбинацию конуса с углом раскрытия 60 градусов и цилиндра и устанавливались в рабочей камере, отделенной от ударной трубы тонкой диафрагмой, закрывающей вход в плоское сверхзвуковое сопло, находящееся в рабочей камере. Модели с тепловыми датчиками на основе анизотропных термоэлементов из висмута размещались в выходном сечении сопла. Сравнение экспериментальных результатов с теоретическими оценками теплового потока, выполненными на основе метода эффективной длины, демонстрирует корректность используемой методики обработки электрического сигнала датчиков на анизотропных термоэлементах и их перспективность в качестве диагностического средства для измерений тепловых потоков при обтекании моделей.

Ключевые слова: тепловой поток, ударная труба, высокоскоростное течение, датчик теплового потока на анизотропных термоэлементах, градиентный датчик теплового потока

Ссылка при цитировании: Монахов Н.А., Сахаров В.А., Попов П.А. Измерение теплового потока при высокоскоростном обтекании осесимметричного тела с помощью датчиков на анизотропных термоэлементах // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2023. Т. 16. № 1.1. С. 450–455. DOI: https://doi.org/10.18721/JPM.161.177

Introduction

Studies of high speed flows around various models are usually carried out using pulsed gas-dynamic facilities, for example, shock tubes with a nozzle. The characteristic stationary flow time (“test time”) in this case is 0.1–10 ms. The heat flux to the body surface is an important measured parameter in a gas-dynamic experiment. Serious requirements are imposed on heat flux sensors in terms of dimensions, mechanical and thermal stability, sensitivity, speed, and noise immunity. Usually, thin-film resistance sensors and coaxial thermocouples are used for such measurements. St. Petersburg Polytechnic University has developed heat flux sensors based on anisotropic thermoelements called “gradient heat flux sensor” (GHFS) [1–3]. Experiments on shock tubes of Ioffe Institute demonstrated their high speed performance, sufficient mechanical strength, and reliability of the obtained results [4–6]. The method for calculating the heat flux from an electrical signal of a single anisotropic thermoelement under non-stationary thermal conditions was proposed at [7]. This method is based on a one-dimensional model of thermal and thermoelectric processes in thermoelements. The main objective of this work is to experimentally verify method proposed in [7] and analysis of its applicability in experiments on shock tubes. As a test problem, a classical gas-dynamic problem of heat transfer on the conical surface of an axisymmetric body in a high-speed gas flow was chosen, which has a well-known theoretical solution.

Sensor description

Figure 1 shows schematically the structure of the sensor based on anisotropic thermoelements. The sensitive element of these sensors is a battery of anisotropic thermoelements made of a single crystal of bismuth, fixed on a mica substrate (2) and separated from each other by lavsan strips (3) (Fig. 1, *a*). The ends of adjacent thermoelements are connected by soldering (4). Wires (5) are soldered to the outside thermoelements for connection to an oscilloscope. The anisotropic thermoelement is a bismuth parallelepiped cut at angle $\theta \approx 45^\circ$ to the crystallographic axes (Fig. 1, *b*). This leads to the appearance of off-diagonal elements of the thermopower tensor. When the thermoelement is heated and a temperature gradient appears, the longitudinal and transverse components of the thermoelectric field vector arise. The generated voltage is determined from the contacts located on the side faces.

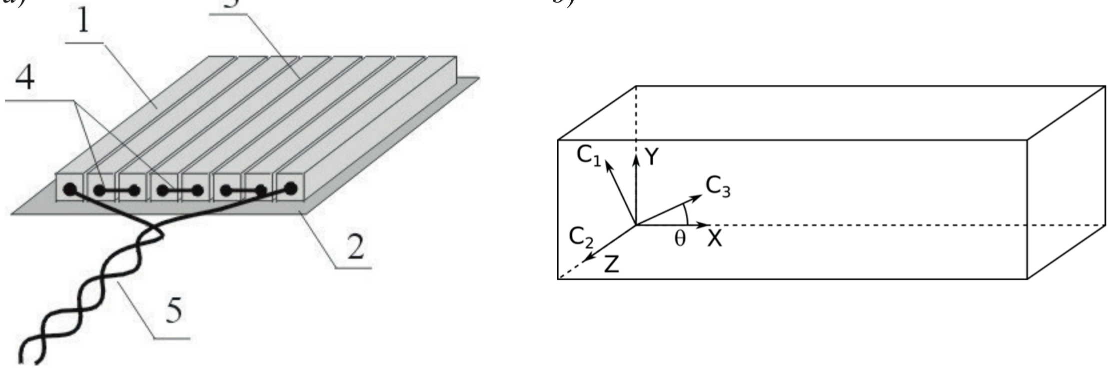

Fig. 1. Scheme of sensor based on anisotropic thermoelements (*a*); Anisotropic thermoelement in two coordinate systems: laboratory (*x*-*y*-*z*), crystallographic (C_1-C_2-C_3) (*b*)

A short response time of ~ 10 ns [8] makes it possible to use these sensors in shock tube experiments with characteristic times of 1 ms. The thickness of the sensor anisotropic thermoelements used in this work was 0.2 mm; therefore, the time to establish the stationary thermal regime ~ 100 ms significantly exceeded the characteristic gas dynamic time ~ 1 ms, and the temperature distribution over the thermoelement was nonlinear [9]. In this case, the heat flux ceases to be proportional to the sensor signal and mathematical processing of its signal is required [7]. The temperature distribution in the two-layer structure “thermoelement-substrate” was calculated using the one-dimensional non-stationary heat conduction equation:

$$C\rho\frac{\partial T}{\partial t}=\frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right), \tag{1}$$

with the boundary condition relating the change in the temperature of the working surface of the sensor $T_h(t)$ to the electrical signal $U(t)$, recorded in the experiment:

$$T_h^{i+1}(t)=T_0^i(t)+\frac{h}{k\lambda nlw}U(t), \tag{2}$$

where T_0 is the temperature of the back surface of the thermoelement, k is the stationary calibration coefficient of the sensor, n is the number of thermoelements in the sensitive element of the sensor, l and w are the length and thickness of the thermoelements. Further, using the known temperature distribution $T(x, t)$, we calculated the heat flux $q_h(t)=\lambda\left.\frac{\partial T}{\partial x}\right|_{x=h}$ passing through the working surface of the sensor. As shown at [7], the relative error of this method is mainly determined by length to thickness ratio of anisotropic thermoelement, and it doesn’t exceed 10% even for rather short thermoelements with $l/h = 10$. Calibration coefficient k can be determined using method described at [3] and the uncertainty of its determination doesn’t exceed 3%.

Experimental setup

The experiments described in this paper were carried out on the Big Shock Tube (BST) [10]. The total length of the BST is 16 m, the pressure chamber is 3 m, and its inner diameter is 100 mm. The models used for experiments were the combinations of a cone with an opening angle of 60 degrees and a cylinder. They were installed in a working chamber separated from the shock tube by a thin diaphragm that closed the entrance to a flat supersonic nozzle located in the working chamber. The model with heat flux sensors was placed in the outer section of the nozzle.

Figure 2 shows the models with thermal sensors 2.2×2.2 mm in size and 0.2 mm thick anisotropic thermoelements installed along the generatrix. The volt-watt ratio of the sensors used was in the range of 12–15 mV/W. In the first series of experiments, a plexiglass model with 6 sensors based on anisotropic thermoelements was used. The distances from the top of the cone to three sensors on the conical surface were 6, 18, and 30 mm, respectively. In the second series of experiments, a metal model with two sensors was used. The distance from the top of the cone to heat flux sensor at the cone generatrix was 15 mm.

In these experiments, hydrogen was used as driver gas, and argon was used as driven gas. The Mach number at the nozzle exit M = 5 was calculated from the ratio of the areas of the nozzle

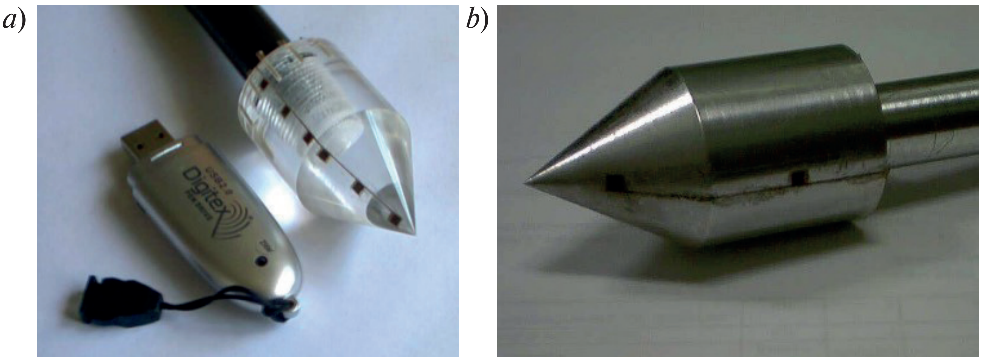

Fig. 2. Plexiglass model with six heat flux sensors (*a*) and the metal model with two heat flux sensors (*b*)

inlet and outlet. Table 1 lists the parameters of experiment. 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 230 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 argon behind the reflected shock wave were determined from the known Mach number and initial pressure in the driven tube using Cantera which is an open-source suite of tools for problems involving chemical kinetics, thermodynamics, and transport processes [11]. Free stream parameters at the nozzle outlet were calculated using the model of one-dimensional stationary expansion in the nozzle.

Table 1

Gas parameters in driven tube and in free stream

Gas	Driven tube					Free stream parameters		
	Incident parameters		Parameters behind reflected shock wave					
	P_1, mbar	M_1	P_5, kPa	ρ_5, kg/m^3	T_5, K	P, kPa	ρ, kg/m^3	T, K
Ar	47	4.32	543	0.664	3972	2.052	0.024	423

During the experiments, it was found that in the case of a plexiglass model, spontaneous “splashes” occur in the electrical signal of the sensor (Fig. 3). The performed analysis showed that this phenomenon is a consequence of the accumulation of static electricity on the model surface, which occurs when a gas flows around the model [12]. The cause of this charge may be small fragments of a plastic diaphragm that at the initial moment closes the supersonic nozzle inlet. During the test time, these fragments become electrified and transfer part of the charge to the model surface upon contact with the model. In some cases, the charge drains along the measuring circuits of the heat flux sensor, causing the appearance of impulse pickups. It was found that the conical surface of the model is most often affected by this effect. The cylindrical surface of the model is much less susceptible to such splashes and the noise level turned out to be within the measurement errors, despite the fact that the signal level of the heat flux sensors located on the cylindrical surface is approximately an order of magnitude lower. When the sensors were installed on a grounded metal model, no such features were observed. Therefore, further results were obtained using a metal model.

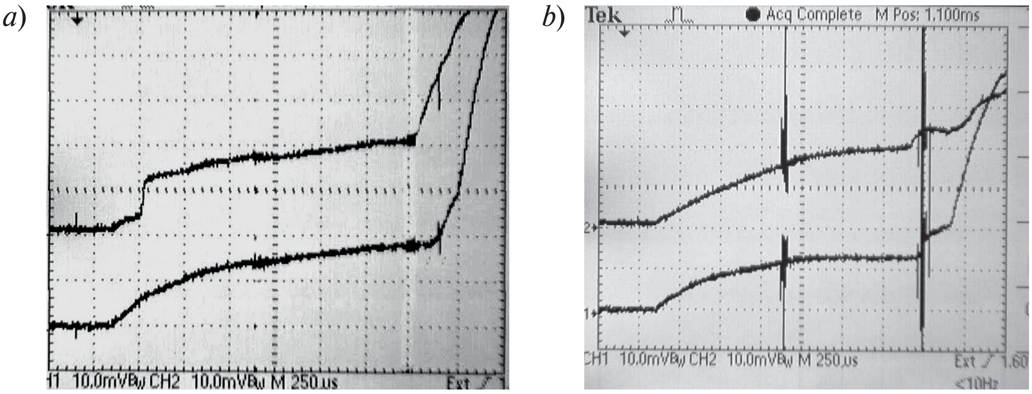

Fig. 3. Typical oscillograms of the heat flux sensor (installed on the conical surface) signal distorted by impulse noise

Results

Fig. 4a shows the electrical signals of the sensors prepared for heat flux calculation. In these experiments, the signal-to-noise ratio is much higher than in previous experiments on measuring the heat flux upon the shock wave reflection [4]. Fig. 4, b shows the heat fluxes calculated from the electrical signal of the sensors. The vertical dotted lines show the test time which corresponds to the stationary flow around the model. Due to the fig. 4, b, an increase in the heat flux during

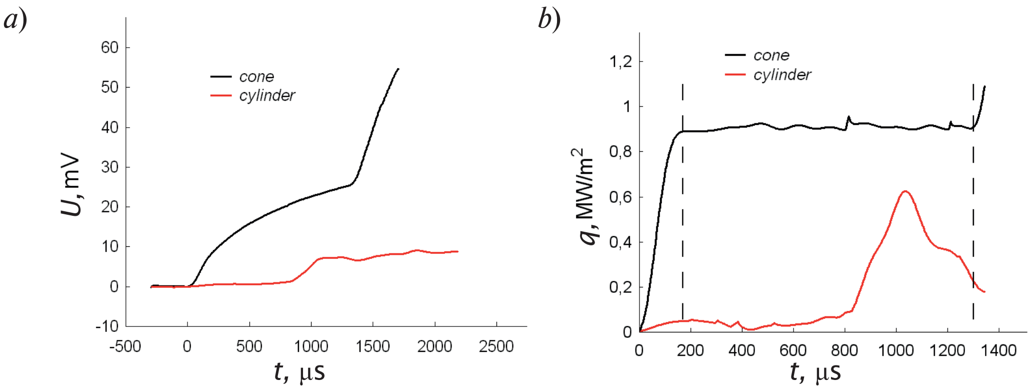

Fig. 4. Electrical signals of heat flux sensors on metal model (*a*); Heat fluxes calculated from sensor signals on metal model (*b*)

the first 200 µs corresponds to the stage of establishing a stationary flow around model and the formation of thermal boundary layer. Further, the period of quasi-stationary flow around the model is about 1000 µs. The heat flux to a cylindrical surface is much less than to a conical one.

The heat flux to the conical surface of the model was estimated using the effective length method. The main idea of this method is that the heat flux at any point on the body surface of arbitrary shape is determined by the thickness of the boundary layer and the shape of the temperature profile in a given section. The effective length is the length of a flat plate, on which, with an external flow with the same parameters as at the considered point of the body, the same thermal boundary layer is formed. Then, for bodies of simple geometry, the expression for the heat flux density is reduced to the expression for the heat flux density on the plate surface in a high-speed flow:

$$q = 0.332\sqrt{\frac{\mu_w \rho_w u_1}{x}}C_p\left(T_e - T_w\right)\mathrm{Pr}^{-2/3}. \tag{3}$$

Here μ_w, ρ_w are gas viscosity and density near the body surface, u1 is longitudinal component of the flow velocity outside the boundary layer, C_p is argon specific heat, T_e is flow stagnation temperature, Tw is wall temperature, Pr is Prandtl number, x is longitudial coordinate. Avduevsky [13] shows that for cones with a high-speed flow around at zero angle of attack, the heat flux can be calculated using relation (3), if we replace the value x in it with $x_{eff} = x/3$, that is, the value of the local heat flux density on the cone is √3 times greater than on a plate of the same length and with the same flow parameters outside the boundary layer:

$$q_{cone} = 0.332\sqrt{\frac{\mu_w \rho_w u_1}{x/3}}C_p\left(T_e - T_w\right)\mathrm{Pr}^{-2/3}. \tag{4}$$

In calculations of the heat flux using formula (4), the specific heat of argon and the Prandtl number were considered constant, since the stagnation temperature does not exceed 4500 K. The surface temperature of the model T_w = 290 K was considered constant during the flow test time, the viscosity of argon at this temperature is $2.23 \cdot 10^{-5}$ Pa·s. Heat flux calculation using relation (4) gives us the value q_{cone} = 763 kW/m^2, while the averaged over the test time measured heat flux value is $q_{cone}^{\exp}$ = 910 kW/m^2. The difference between these values may be due to the uncertainty of the stationary calibration of heat flux sensors (according to [3], it does not exceed 3%), the error in calculating the heat flux using a one-dimensional model of anisotropic thermoelements (according to [7], it does not exceed 10%), as well as the error in determining the parameters of high-speed flow near the model.

Conclusion

The results of measuring the heat flux by sensors based on anisotropic thermoelements with an external high-speed argon flow around a conical model are presented. The experimental results are compared with the theoretical estimates of the heat flux made on the basis of the effective length method [13]. The relative difference between the measured and calculated heat fluxes, which does not exceed 15%, demonstrates the correctness of the electrical signal processing technique used and the prospects of a sensor based on anisotropic bismuth thermoelements as a diagnostic tool for measuring heat fluxes in high-speed flows around models.

REFERENCES

1. **Sapozhnikov S.Z., Mityakov V.Y., Mityakov A.V.,** Gradient heat flux sensors for high temperature environments, 2004 High Temperature. (2004) 629–638.
2. **Mityakov A.V., Sapozhnikov S.Z., Mityakov V.Yu., et al.,** Gradient heat flux sensors for high temperature environments, Sens. and Act. A: Phys. 176 (11) (2012) 1–9.
3. **Sapozhnikov S.Z., Mityakov V.Yu., Mityakov A.V.,** Heatmetry: The Science and Practice of Heat Flux Measurement, Springer International Publishing, 2020.
4. **Popov P.A., Sakharov V.A., Poniaev S.A., et al.,** Heat flux measurement at the initial phase of normal shock wave reflection using the sensor on anisotropic thermoelements, J. Phys. Conf. Ser.1697 (2020) 012225.
5. **Popov P.A., Monakhov N.A., Kotov M.A., Poniaev S.A.,** Experimental investigation of the thermal loads upon electrodynamic modification of supersonic flow around axisymmetrical body, IOP Conf. Ser.: Mater. Sci. Eng. 927 (2020) 012084.
6. **Kotov M.A., Shemyakin A.N., Solovyov N.G., et al.,** Performance assessment of thermoelectric detector for heat flux measurement behind a reflected shock of low intensity, Appl. Therm. Eng. 195 (2020) 117143.
7. **Popov P.A., Bobashev S.V., Reznikov B.I., Sakharov V.A.,** A Method of Nonstationary Heat Flux Calculation Using the Signal of a Sensor Based on Anisotropic Bismuth Single-Crystal Thermoelements, Tech.Phys.Letters 44 (2018) 316–319.
8. **Bobashev S.V., Mende N.P., Sakharov V.A., Sappozhnikov S.Z., Mityakov V.Yu., Mityakov A.V., Van Wie D.V.,** Application of Gradient Heat Flux Sensor in Shock Tube Experiments, Proc. 43rd AIAA Aerosp. Sci. Meeting and Exhibit (Reno) (2005).
9. **Popov P.A., Bobashev S.V., Reznikov B.I., Sakharov V.A.,** The influence of thermophysical substrate properties of an anisotropic thermoelement on thermopower in the nonstationary thermal regime, Tech. Phys. Lett. 43 (4) (2017) 334–337.
10. **Maslennikov V.G., Sakharov V.A.,** Double-diaphragm shock tube at the Ioffe Physicotechnical Institute, Tech. Phys. 42 (1997) 1322–1328.
11. Cantera – open-source suite of tools for problems involving chemical kinetics, thermodynamics, and transport processes. https://cantera.org/. Accessed Aug. 14, 2022.
12. **Kuribayashi T., Ohtani K., Takayama K., et al.,** Heat flux measurement over a cone in a shock tube flow, Shock Waves 16 (2007) 275-285.
13. **Avduevsky V.S. et al.,** Osnovy teploperedachi v aviatsionnoi I raketno-kosmicheskoi technike, Mashinostroenie, Moscow, 1992. (in Russian).

THE AUTHORS

MONAKHOV Nikolay A.
nikolay.monakhov@mail.ioffe.ru
ORCID: 0000-0003-0585-3320

POPOV Pavel A.
Pavel.popov@mail.ioffe.ru
ORCID: 0000-0002-3843-3616

SAKHAROV Valerii A.
v.sakharov@mail.ioffe.ru

Received 26.10.2022. Approved after reviewing 08.11.2022. Accepted 08.11.2022.