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Pulse thermal load for thermoelectric detector calibration

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Abstract. The work is devoted to the calibration of the developed thermoelectric detectors with different sensitive elements. A pulsed laser diode with a power of 5 W was used as a radiation source. A lamp with a tungsten filament was also used to set the combined thermal load and assess the overall level of sensor sensitivity. The performed calibration procedures made it possible to obtain volt-watt characteristics for thermoelectric detectors of a new type, which will help to better describe the thermal processes of high-intensity shock-wave interactions occurring in a pulsed gas-dynamic experiment.

Keywords: heat flux, shock tube, laser heating, calibration

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Импульсная тепловая нагрузка для калибровки термоэлектрического детектора

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Аннотация. Работа посвящена калибровке разработанных термоэлектрических детекторов с различными чувствительными элементами. В качестве источника излучения использовался импульсный лазерный диод мощностью 5 Вт. Лампа с вольфрамовой нитью также использовалась для установки комбинированной тепловой нагрузки и оценки общего уровня чувствительности датчика. Выполненные калибровочные процедуры позволили получить вольт-ваттные характеристики термоэлектрических детекторов нового типа, которые помогут лучше описывать тепловые процессы высокоинтенсивных ударно-волновых взаимодействий, происходящих в импульсном газодинамическом эксперименте.

Ключевые слова: фазовый тепловой поток, ударная труба, лазерный нагрев, калибровка

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Introduction

Surface temperature and heat flux measurements play a very important role in heat transfer studies. Registration of changes in heat fluxes in a gas-dynamic experiment during ultra-short time periods is one of the most significant factors in setting up and conducting studies of heat transfer in pulse supersonic and hypersonic flows. Typical time values in such gas dynamic experiments range from hundreds of microseconds to several milliseconds. In shock tube experiments [1–4], the model is subjected to a sudden high thermal load on a very short measurement time scale. To calibrate the thermal sensors for such free flow conditions, experiments are carried out by applying a thermal load from a laser beam with a known output power [4–6]. For pulsed gas dynamic processes, the laser calibration method is the most suitable, since it allows the desired value of the heat flux to be applied to the sensor very quickly. The emitted power value used is fixed and can change rapidly during the calibration process. The resulting volt-watt characteristic of the sensor is used for its subsequent application under the considered gas flow regimes – short time intervals and high temperature loads.

This work is devoted to the calibration of thermoelectric detectors [7–9] with different sensitive elements. A laser diode (975 nm) were used as a radiation source in the calibration stand. A pulsed operation mode was set at a radiation power of 5 W. Solution of issues related to radiation homogenization makes it possible to obtain reliable calibration dependences. To control the response time of the sensor and signal rise fronts, a high-speed photodiode with a time resolution of less than 20 ns was placed in the optical scheme of the stand. In addition to laser devices, a lamp with a tungsten filament was also used to set the combined thermal load and assess the overall level of sensor sensitivity.

The performed calibration procedures made it possible to obtain volt-watt characteristics for thermoelectric detectors of a new type, which will help to better describe the thermal processes of high-intensity shock-wave interactions occurring in a pulsed gas-dynamic experiment.

Creation of two types of thermoelectric detector

The principle of operation of thermoelectric detectors is based on the generation of thermo-EMF when a temperature gradient occurs in the sensitive element with anisotropy of the coefficient. The method used under the conditions described above for measuring transient temperature with surface transient sensors should have a fast response time and be adequate for rapidly changing flow conditions. As a surface heat flux sensor, these devices are suitable for measuring high power transient heat flux. In [7, 8], such sensors showed good results in measuring heat fluxes in shock tubes with shock waves of low and high intensity. The obtained values reached more than 45 MW/m^2 for 1 μs with a registration frequency of 10^7 Hz and a high signal-to-noise ratio, and the environments of the sensors were quite aggressive.

For this work, two sets of sensors with different sensitive elements were manufactured. They were based on a silicon layer 0.4 mm thick, thermally oxidized on both sides and having a high resistance. A film of an oblique anisotropic layer 0.3 μm thick in the form of an inclined columnar structure is deposited on the front side of the sensor by vacuum deposition. For the first set, this was the Cr layer. The second set used the GeTe alloy. On the sides of the sensing element there were contact pads through which the thermo-EMF was taken.

Lamp calibration

In this method, heat transfer occurs due to broadband thermal radiation. The purpose of the procedure was to evaluate the overall level of sensitivity of the manufactured sensors. The sensitive elements were placed on an Al substrate. To ensure heat dissipation, a layer of thermal paste is applied between the sensor and the substrate. A constant heat flux to the plane of the sensitive element was provided by a tungsten lamp. To register the sensor readings, a V7-40 microvoltmeter was used. After turning on the lamp, the readings of the microvoltmeter were set to a certain maximum value for the sensor under test. The time to reach the maximum value was approximately 1 s. Then the lamp was turned off, the heat flux sensor was replaced by the next one (Cr and GeTe, 6 sensors in each set) and the procedure was repeated. Table 1 shows the obtained values. The sensitivity level of GeTe sensors exceeds Cr by several orders of magnitude. At the same time, the sensitivity of elements in one set can differ by dozens (more than 40 times for Cr and more than 8 times for GeTe, see Table 1). It depends on the deposition density of the sensitive element.

Table 1

Lamp calibration results for Cr and GeTe sets

r	#1	30 μV	x_1	GeTe	#1	10 mV	x_2
	#2	40 μV	$1.2 \cdot x_1$		#2	18 mV	$1.8 \cdot x_2$
	#3	50 μV	$1.6 \cdot x_1$		#3	42 mV	$4.2 \cdot x_2$
	#4	200 μV	$6.6 \cdot x_1$		#4	45 mV	$4.5 \cdot x_2$
	#5	280 μV	$9.3 \cdot x_1$		#5	48 mV	$4.8 \cdot x_2$
	#6	580 μV	$19.3 \cdot x_1$		#6	64 mV	$6.4 \cdot x_2$
	#7	1.25 mV	$41.6 \cdot x_1$		#7	81 mV	$8.1 \cdot x_2$

Laser diode pulses

The stand for measuring sensors is shown in Fig. 1, *a*. A laser diode PLD-10 975 nm with optical fiber of 0.13 NA was used as a radiation source. The fiber output is set at a distance of 40 mm from the sensor. The sensor was located at the bottom of the stand and covered with a special Al mask (0.7 mm thick with 3 mm hole at center) for thermal load set directly on sensitive element and to ensure that there was no thermal effect on the contact pads (Fig. 1, *b*). Hantek DSO5202P digital oscilloscope was used for data registration.

The sensor is mounted on a 2 mm thick duralumin heat-removing plate through a thin layer of thermal paste. The signal to the oscilloscope was taken directly from the sensor, the probe resistance is 1 MOhm (the standard probe for this oscilloscope), a 1 kOhm resistor is installed in parallel with the sensor. To evaluate the speed of the laser diode, an SFH203P photodiode with a rise and fall time of 5 ns in the voltage generation mode was used. The result is shown in Fig. 2. The rise and fall time of the laser diode is approximately 1 μs.

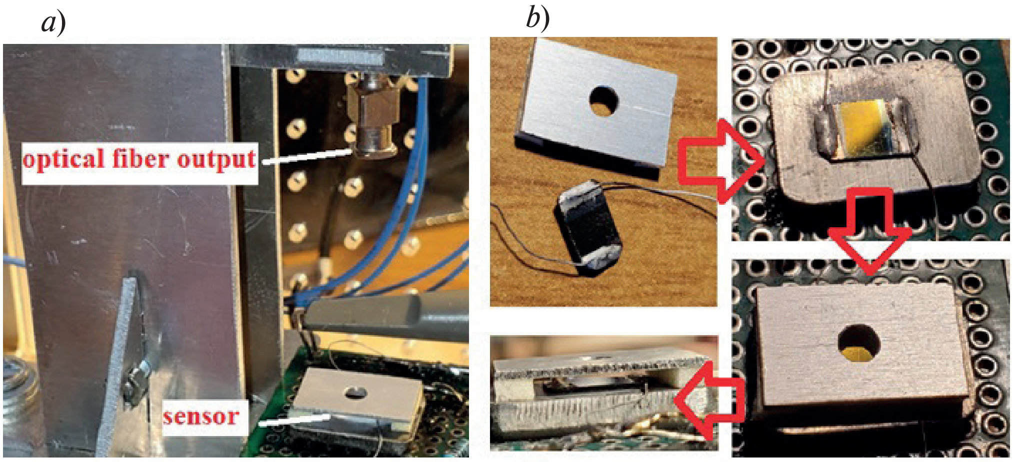

Fig. 1. Laser diode stand (*a*); The procedure for installing the sensor with Al mask (*b*)

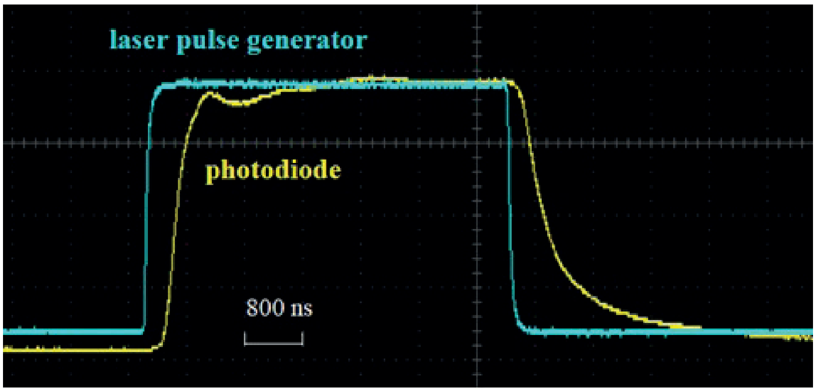

Fig. 2. Data (a.u.) from laser pulse generator (blue) and photodiode at sensor plate (yellow)

To comply with the conditions for correct calibration by laser radiation, it is important to ensure its instantaneous and uniform absorption directly on the sensitive element of the sensor being calibrated. It is also necessary to ensure that radiation does not pass through the sensitive element due to its possible absorption/dissipation in other places of the sensor. For these purposes, a thin layer (~ 20 μm) of black matte nitro paint was applied. The radiation absorption coefficient was considered equal to 0.9, which can be set as valid for a wavelength of 975 nm and such environmental conditions. Some results obtained with a laser pulse duration of 500 μs and a repetition rate of 100 Hz are shown in Fig. 3.

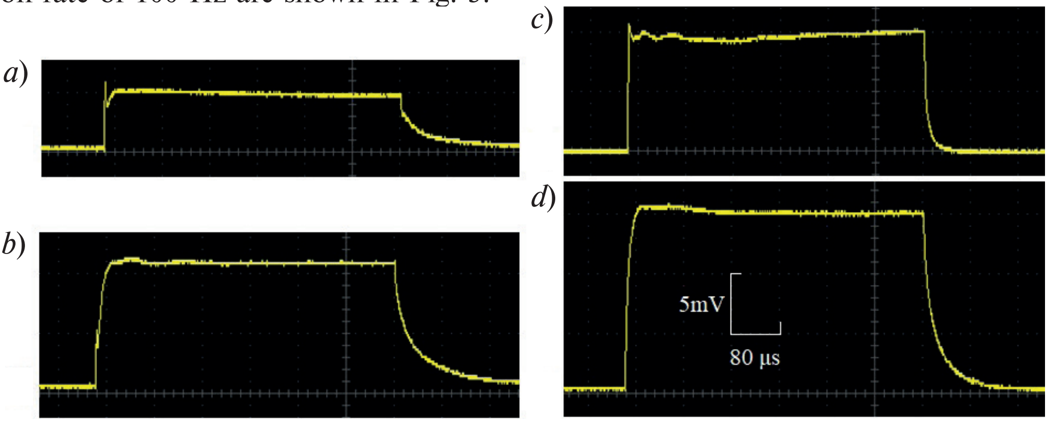

Fig. 3. Signals for #1 (*a*), #2 (*b*), #4 (*c*) and #7 (*d*) GeTe sensors from 500 μs laser pulse heat load

Cr-based sensors have a significantly lower sensitivity; therefore, to study their characteristics, an amplifier with a voltage amplification factor of 50 was used. The performance of the amplifier was tested using the GK101 pulse generator at 1—100 kHz rate.

The value of the power coming to the sensor can be estimated as follows. Let's assume that the distribution profile of the radiation intensity of the multi-mode fiber is uniform. Knowing the numerical aperture (0.13) and the distance to the sensor mask (40 mm), we can calculate the laser spot diameter — 10.5 mm. The power of the radiation incident on the sensor through the mask is approximately equal to the ratio of the output power from the optical fiber (5 W) to the ratio of the areas of the laser spot and the mask hole (3) — 1.66 W. Estimates of the calibration coefficient for manufactured sensors are given in Table 2.

Fig. 3 shows that the exposure time of the laser diode is sufficient to establish a quasi-constant value in the sensor readings. The long rising and falling fronts of signals can be explained by the heating and cooling time of the black paint layer that absorbs radiation. The discrepancy between the coefficients at tables 2 and 1 is up to 5 times for cases with sensors that show the largest signal. The reasons explaining that may be the following:

- The lamp has a broadband spectrum in contrast to the monochromatic radiation of a laser diode. The principle of sensors operation is based on the occurrence of thermal emf, however, radiation at different wavelengths can heat the sensitive element in different ways.

Table 2

Laser pulse calibration results for Cr and GeTe sets

Cr	#1	0.28 mV	x_1	GeTe	#1	5 mV	x_2
	#2	0.3 mV	$1.1 \cdot x_1$		#2	9 mV	$1.8 \cdot x_2$
	#3	0.67 mV	$2.4 \cdot x_1$		#3	11 mV	$2.2 \cdot x_2$
	#4	0.98 mV	$3.5 \cdot x_1$		#4	11.5 mV	$2.3 \cdot x_2$
	#5	1.37 mV	$4.9 \cdot x_1$		#5	12 mV	$2.4 \cdot x_2$
	#6	2.43 mV	$8.7 \cdot x_1$		#6	14.5 mV	$2.9 \cdot x_2$
	#7	4.87 mV	$17.4 \cdot x_1$		#7	17 mV	$3.4 \cdot x_2$

- No absorbent paint was applied in procedure with the lamp (Section 3), so readings are slightly high.
- On the other hand, the action with a laser diode is limited to a round spot with a diameter of ~ 3 mm instead of no limitation in the case of a lamp, which affects the signal in the direction of decreasing. Typical values for the areas of sensitive elements of manufactured sensors lie in the range from 3.5×3.5 mm^2 to 4.5×4.5 mm^2. Those, the areas of thermal impact can differ by 1.5–2.5 times. At the same time, this difference can be neglected, because the full heating of the black paint layer is still carried out, and this rather affects the growth of the readings, but not their steady value.
- The same can be said about the possible uneven distribution of radiation power in the laser spot and other inhomogeneities.
- Despite the high signal-to-noise ratio, the presence of noise contributes to the error in the readings of the sensors. This is especially true in the case of Cr sensors and laser heating, when an amplifier was used due to small values and the noise level was high.

The heat flux density in mask experiments is approximately 8.3 W/cm^2 with an average sensing element area of 20 mm^2. The values of x_1 and x_2 for Table 2 can be estimated at $3.3 \cdot 10^{-9}$ V·m^2/W and $6 \cdot 10^{-8}$ V·m^2/W, respectively, which looks similar to the data obtained in [7] during shock tube calibration. It can be said that this procedure is suitable for calibration of thermoelectric detectors for the purpose of their further application in the pulse gas-dynamic experiment. However, there are several points that may affect the differences in the resulting calibration rates:

- The radiation power value of 5 W was set with high accuracy at the input to the optical fiber of the laser diode. It was assumed that there was no absorption of radiation in fiber, however, with long fibers it can be up to several percent.
- Fiber multimode, inhomogeneity of the power profile distribution in the laser spot, other peculiarities also affect the values of the radiation power directly at the input of the sensor.
- The generation of thermo emf with such short structures may have a non-linearity as the heat flux increases/decreases. At tens of W/cm^2, a good agreement is observed, but for higher/lower thermal loads, it is advisable to perform separate calibrations.

Conclusion

Cr-based thermoelectric detectors have been manufactured, which have shown their effectiveness in measuring the heat flux in a pulsed gas-dynamic experiment in [7–9]. A new type of sensors based on GeTe has been developed. The calibration procedures (lamp calibration and laser pulse) carried out in this work made it possible to obtain reliable estimates of the volt-watt dependencies. The data obtained for different types of sensors and calibration procedures are in good agreement both with each other and with previous experiments. This allows one to speak about the suitability of such procedures for obtaining calibration characteristics. Aspects that may affect the discrepancy in the received data are described.

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