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Registration of radiative heat flux in a shock tube using a thermoelectric detector

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The results of experimental studies on registration of the radiative component of the total heat flux by a thermoelectric detector in a reflected shock wave are presented. An increase in the contribution of radiation to the heat flux with an increase in the intensity of the shock wave is estimated. It is shown that the technique can be used in experiments in shock tubes to isolate the radiative component of the total heat flux, and the thermoelectric detector itself can be successfully used to record such parameters.

Keywords: shock tube, thermoelectric detector, radiation heat transfer.

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The interest in construction of new spacecraft and development of projects for further study of planets of the Solar System is growing steadily. The set of issues concerning the characteristics of a plasma layer produced near the surface of a landing module moving through the atmosphere belongs to a class of problems that are highly relevant today. The total heat flux to the spacecraft surface at high flight speeds has a considerable radiative component, which depends on the emissivity and absorptivity of the emerging plasma layer [1]. A reliable evaluation of convective and radiative heating components in produced shock-wave structures is of both fundamental (in relation to the study of high-speed gas dynamics and physicochemical kinetics [2,3]) and applied (in the prospect of determination of the thermochemical properties of heat-protection materials and engineering of spacecraft modules [4–7]) importance.

Gas-dynamic facilities such as shock tubes are used to model these conditions on the Earth, since they provide high levels of enthalpy of an incoming gas flow (up to 60 MJ/kg or more [1]). However, the operating regime is maintained for just several milliseconds in such setups [8], and strict requirements are thus imposed on detection methods. The measurement of radiation intensity by various optical circuits and receivers, which are normally tuned to a wide 300−1100 nm band or certain regions of it, is understood as the determination of radiation characteristics in these experiments. Recent studies [9] have demonstrated that thermoelectric detectors are capable of detecting radiation in the process of self-ignition of a combustible mixture in an incident shock wave.

Either specialized sensors with different operation mechanisms [10,11] or temperature-sensitive coatings [12] are used to determine experimentally the heat flux in pulsed gas-dynamic processes. One of the key problems in arranging such an experiment consists in insufficiency of the sampling rate (below 1 MHz): a heat flux at the collecting aperture of a sensor or a coating averaged over several milliseconds is determined in direct measurements. The sensing element of a thermoelectric detector has a thickness of $0.3\,\mu$m and a collecting aperture of 4×4 mm and is composed of chromium crystallites with insignificant spatial misalignment deposited onto a silicon substrate. Owing to their oblique structure, a thermal emf component arises between the outer and inner surfaces of a heated sensing element; it is projected across the substrate and picked up from contact pads on the sides of a detector. A thin sensing element allows this sensor to sample the total heat flux at a rate in excess of 10 MHz under fairly extreme conditions (a temperature higher than 10^4 K [13] and a pressure above 30 atm [9]).

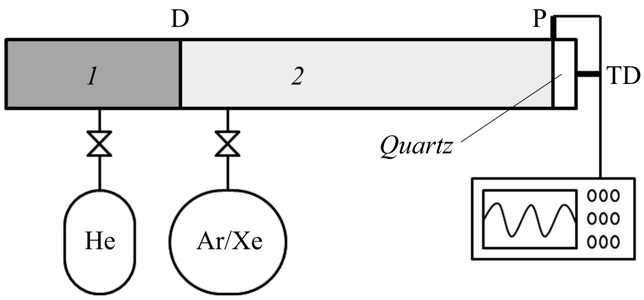

Figure 1. Shock tube diagram. High- and low-pressure chambers (*1* and *2*) are separated by diaphragm D. Pressure sensor P determines the moment of arrival of an incident SW to a quartz wall (*Quartz*), and thermoelectric detector TD measures the heat flux.

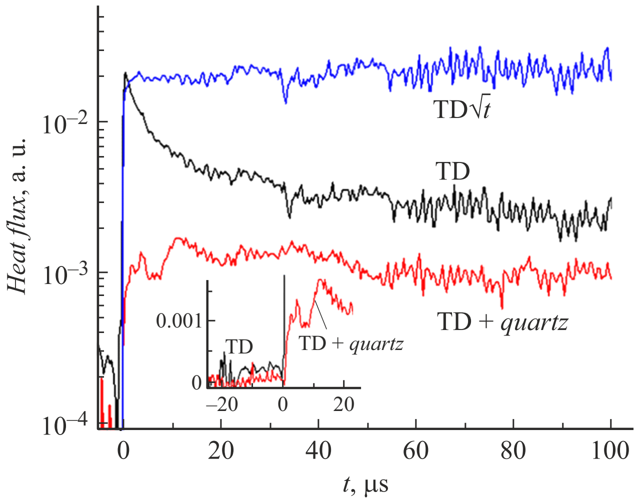

Figure 2. Measurement of the heat flux in argon behind a reflected SW. TD — Thermoelectric detector readings; TD$\sqrt{t}$ — TD data multiplied by the square root of time; TD + *quartz* — data with the quartz insert. The initial argon pressure is 0.1 atm at 293 K, and the incident SW speed is 1 km/s.

Radiation produces a significant contribution to heat transfer processes when the gas temperature behind the front of a shock wave (SW) becomes sufficiently high (above several thousand kelvins). Obliquely deposited thermoelectric detector films offer a high sensitivity to an instantaneous heat impact, since their thin oblique structure produces a significant thermal emf signal. Importantly, a sensing element of this kind generates a signal for both convective and radiative heat fluxes. The operating principle of the sensor and its characteristics were examined in more detail in [9,13–15]. The total heat flux is measured this way.

Thermoelectric detectors are calibrated by heating with a filament lamp or a laser diode; experiments in a shock tube with a reference sensor and subsequent comparison of the obtained values of the heat flux behind an SW may also be performed. Calibration procedures were described more thoroughly in [9,15,16]. A sensor without a calibration coefficient was used in the present study. The presented values in arbitrary units are proportional to the heat flux expressed in W/m^2.

Experiments on isolation of the radiative heat flux component were carried out in a shock tube operating behind a reflected SW. The diagram of the setup is shown in Fig. 1. A series of experiments with similar initial conditions were performed. In some of them, an optical quartz glass insert with a transmission coefficient remaining above 95% in the 400–1000 nm range (even at high temperatures [17]) was mounted in front of the detector surface to cut off the convective heat flux. The results of measurement of the heat flux from an incident low-intensity shock wave (the SW speed was 1 km/s) in argon are presented in Fig. 2.

Data are presented without regard to the amplitude-frequency response. The radiative heat flux (TD + *quartz*) measured by the thermoelectric detector is much lower than the total heat flux (TD). At the moment of SW reflection off the end wall of the tube (point $t = 0$ in Fig. 2) the TD and TD + *quartz* readings differ by a factor of more than 20, indicating that the radiative contribution to the total heat flux is small. Similar experiments were performed in argon at higher incident SW speeds. The obtained results reveal a gradual enhancement of the radiative heat flux component with increasing SW speed, since the intensity of emission of shock-heated argon increases (especially in the visible range [18]).

It is convenient to use a normalized heat flux, which depends only on the parameters of gas behind a reflected SW, to compare experimental and theoretical data and determine the degree of their consistency in the problem of SW reflection off a plane wall [19,20]. It can be seen from Fig. 2 that the corresponding parameter TD$\sqrt{t}$, which represents the thermoelectric detector readings, does not change in any significant way: its mean value remains constant, verifying the validity of the obtained results. This parameter varied in a similar fashion in other experiments.

The results of measurement of the radiative heat flux in xenon behind a reflected SW are presented in Fig. 3. Just as in Fig. 2, the TD + *quartz* data reveal an enhancement of the radiative heat flux occurring immediately after the arrival of an SW and its reflection off the quartz wall. The measured radiative heat flux values are more than three orders of magnitude higher than those determined in argon (Fig. 2, TD + *quartz*), since the temperature of xenon behind a reflected SW is also higher. Pressure sensor P is positioned on the side wall of the shock tube directly in front of the quartz insert (Fig. 1). Therefore, a spike in its readings due to the SW arrival is observed slightly earlier.

The results of experimental studies into the measurement of heat fluxes with a material transparent in a specific spectral range suggest that thermoelectric detectors may be used efficiently to determine the intensity of radiative heat

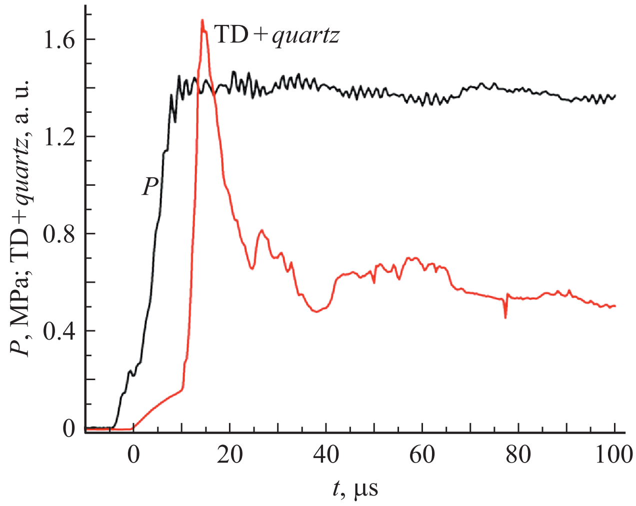

Figure 3. Measurement of the radiative heat flux component and the pressure in xenon behind an SW reflected off the quartz wall (time point of reflection is $t = 0$). The collecting aperture of sensor P is 5 mm, and the incident SW speed is 1.2 km/s.

transfer in the examined physical process. The considered technique may be applied in ground tests in shock tubes to imitate the entry of spacecraft into a dense atmosphere of planets and moons of the Solar System and compare the obtained data with the readings of an onboard radiometer that records the radiative heat flux values in the course of flight and landing [21,22].

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Conflict of interest

The authors declare that they have no conflict of interest.

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