EXPERIMENTAL INVESTIGATION OF TEMPERATURE BEHIND STRONG SHOCK WAVES IN ARGON AT M = 8-30

A. V. Il'metov and V. I. Titov

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Results are presented of a pyrometric investigation of the state of the medium behind the strong shock waves in argon. The experimental data are compared with theory.

In most investigations conducted in shock tubes the parameters of the medium behind the shock are calculated from one-dimensional gasdynamic theory using the conservation laws and equations determining the state, internal energy, and degree of ionization of the gas. This theory implies that the gas behind the shock wave is in thermodynamic equilibrium, and its parameters are uniquely determined by the shock wave speed and the initial conditions. The validity of these hypotheses for incident shock Mach number $M \leq 12$ has been confirmed in [1-4] in temperature measurements using the method of impurity spectral line reversal (sodium or barium) at the shock wave front.

When one investigates plasma flows behind a reflected shock wave with higher incident shock Mach numbers, the temperature and density behind the reflected shock are large, which makes it possible to determine them directly. However, it should be noted that when the test gas is radiating strongly one requires a probe source with high brightness temperature. A pulsed discharge in a capillary with brightness temperature of about 30,000°K in the region $4500 \cdot 10^{-10}$ m was used in [5] to measure the absorptivity. This source was used to measure the temperature behind a reflected shock in air in the range 9000-13,000°K. It was found that for temperatures of 9000-11,500°K there is agreement between experimental data and values calculated from the conservation laws. At higher temperatures the theory is observed to deviate from experiment, but the deviation falls within the limits of measurement. For greater incident shock strength the role of dissipative processes increases, and these are not accounted for in elementary shock tube theory. Interaction of the reflected shock with the boundary layer, together with variation in shock wave speed, leads to the formation of a "bifurcation" zone which alters the nature of the flow [7]. Therefore, it is not sufficiently valid to extrapolate the results obtained in [1-6] to higher Mach number. For this reason in the present paper an experimental determination has been made of the temperature of argon behind a reflected shock in the incident Mach number range 8-30.

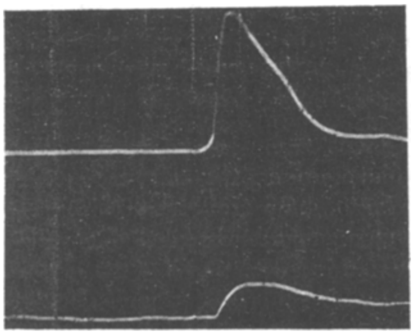

Fig. 1. Oscillogram of the absorptivity and emittivity of the argon plasma behind a reflected shock for M = 20.

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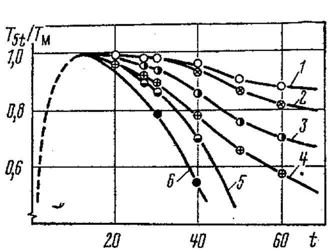

Fig. 2

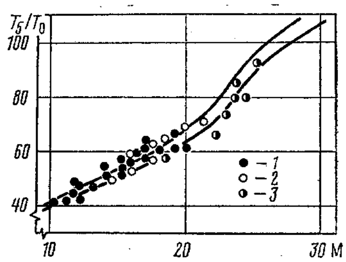

Fig. 3

Fig. 2. Temperature behind the reflected shock wave in argon as a function of time: 1) M = 12; 2) 13; 3) 15; 4) 18; $P_0 = 1.33 \cdot 10^3$ N/m^2; 5) 20; 6) 23; $P_0 = 1.33 \cdot 10^2$ N/m^2; t, 10^{-6} sec.

Fig. 3. Temperature behind the reflected shock wave in argon as a function of incident shock speed: The curves represent theory; 1) the data of [6]; 2, 3) experimental temperature values from the present work for $(10, 1) \cdot 1.33 \cdot 10^2$ N/m^2, respectively.

The experimental arrangement used to obtain the argon plasma has been described in [8].

A major factor in measuring temperature by this method is the choice of probe light source to determine the absorptivity of the hot gas. The use of a capillary pulsed discharge [5] requires accurate synchronization of the discharge with the time of reflection of the shock wave. At temperatures above 12,000°K the self-radiation of the gas is comparable with the capillary radiation. This leads to substantial errors in measuring temperature. These defects were avoided in [6] by using a continuous laser. The brightness temperature of the laser radiation is several orders of magnitude above that of the gas self-radiation. The narrow spectral region and the low divergence of the laser beam allows one to eliminate stray light in the channel recording the gas self-radiation.

The experimental equipment for measuring temperature and the technique for conducting the investigations have been described in [6].

In the tests we used pure argon from metal bottles. According to specifications the bottles contained no more than 0.01% of impurity: of this, nitrogen was no more than 0.008% and oxygen 0.001%. The initial argon pressure in the low-pressure chamber was $(1 \text{ and } 10) \cdot 1.33 \cdot 10^2$ N/m^2. The experimental measurements were taken at distance $(3\text{–}5) \cdot 10^{-3}$ m from the end of the shock tube. This distance between the optical axis and the shock tube end wall was chosen for the following reasons.

First, the maximum distance of the optical axis from the end wall must be less than the distance between the end wall and the point where the reflected shock meets the contact surface. This distance can be evaluated from the length of test gas slug behind the incident shock. The calculation, allowing for the wall layer, shows that the distance between the end wall and the point where the reflected shock meets the contact surface is $(10\text{–}80) \cdot 10^{-3}$ m, depending on the initial pressure in the low-pressure chamber and the incident shock speed. On the other hand, one must eliminate the "bifurcation" region, where there may be nonuniformities in temperature and pressure, and also where particles of impurity from the shock tube end wall may be mixed with the test gas.

Figure 1 is a typical oscillogram showing the emittivity and absorptivity of argon heated by the reflected shock. The upper beam on the oscillogram is the signal from the radiation channel, and the lower beam is the signal from the absorptive channel. The initial pressure in the low-pressure chamber was $1.33 \cdot 10^2$ N/m^2, and the shock tube speed was $6.4 \cdot 10^3$ m/sec.

It can be seen in Fig. 1 that the absorptivity reaches a maximum, and the remains constant for $(20\text{–}30) \cdot 10^{-6}$ sec, within the limits of experimental error. Then it begins to gradually decrease.

For incident shock speeds of $(4.9\text{–}5) \cdot 10^3$ m/sec and above and initial pressure $10 \cdot 1.33 \cdot 10^2$ N/m^2 the absorptivity is 1, within experimental error, and therefore for higher speeds the argon radiates like a perfect black body in parts of the spectrum where there are no impurity lines. With initial low-pressure chamber pressure of $1.33 \cdot 10^2$ N/m^2 one can go on to higher speeds and measure the absorptivity at higher incident shock wave speeds.

The general nature of the oscillograms of emittivity and absorptivity of argon behind the reflected shock wave are maintained at higher incident shock wave speeds.

The results of measurements of time-wise dependence of argon temperature behind the reflected shock wave are shown in Fig. 2 ($P_0 = 1.33 \cdot 10^3$; $1.33 \cdot 10^2$ N/m^2), where the ordinate is the ratio of the temperature at a given time to the maximum temperature. From the figure it can be seen at low Mach number the temperature behind the reflected shock remains constant for a period of $(40-50) \cdot 10^{-5}$ sec. With increase of the incident shock wave speed the time for which the temperature remains constant decreases, and at higher Mach numbers it is $(20-10) \cdot 10^{-6}$ sec.

Figure 3 shows the results of measurements of temperature behind the reflected shock wave. The measured temperature is referred to the first "plateau" in Fig. 2, i.e., to the time where the temperature may be considered constant. The points are the experimentally determined temperature values, and the continuous curve is the theoretical calculation using shock tube gasdynamic theory according to [9]. It can be seen from the figure that the experimental data agree with theory. The calculations allowed for the Debye lowering of the ionization potential.

The results of the investigation can be used for various thermophysical investigations.

NOTATION

T_5 is the temperature behind the reflected shock wave;
T_0 is the initial temperature ahead of the incident shock wave;
T_{5t} is the temperature behind the reflected wave as a function of time;
T_M is the maximum temperature behind the reflected shock wave;
M is the Mach number;
t is the time.

LITERATURE CITED

1. N. N. Sobolev et al., Izv. Akad. Nauk SSSR, Ser. Fiz., 22, 730 (1958).
2. A. G. Sviridonov and N. A. Sobolev, Zh. Eksp. Teor. Fiz., 24, 93 (1953).
3. E. M. Kudryavtsev, N. N. Sobolev, L. N. Tunitskii, and F. S. Faizullov, Tr. Fiz. Inst. Akad. Nauk, 18, 159 (1962).
4. F. S. Faizullov, Tr. Fiz. Inst. Akad. Nauk, 18, 59 (1962).
5. A. A. Kon'kov, A. P. Razin, and V. S. Rudnev, J. Quant. Spectrosc. Radiat. Transfer, 7, 345 (1967).
6. A. A. Kon'kov and S. G. Kulagin, Teplofiz. Vys. Temp., 11, 1062 (1973).
7. T. V. Bazhenova, L. G. Gvozdeva, Yu. S. Lobastov, I. M. Naboko, R. G. Nemkov, and O. A. Predvoditeleva, Shock Waves in Real Gases [in Russian], Nauka, Moscow (1968).
8. A. A. Kozlov and A. L. Il'metov, Inzh.-Fiz. Zh., 28, No. 4 (1975).
9. G. I. Kozlov and E. L. Stupitskii, Tables of Thermodynamic Parameters of Argon and Xenon behind Incident and Reflected Shock Waves [in Russian], AN SSSR, Moscow (1969).