EXPERIMENTAL STUDY OF PRESSURE BEHIND REFLECTED SHOCK WAVES IN ARGON AT MACH NUMBERS OF 10-35

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UDC 533.6.011.72

The results are presented for a study of the pressure behind reflected shock waves for pressures of $(1\text{-}10) \cdot 1.33 \cdot 10^2$ N/m^2 ahead of the incident shock wave. It is found that during the first $1.0\text{-}2.0 \cdot 10^{-5}$ sec after the reflection of the shock wave the pressure of an argon plasma behind it corresponds to that calculated from the conservation laws with allowance for ionization on the assumption that the plasma is ideal.

The conservation laws make it possible to uniquely determine the equilibrium parameters of the medium behind a shock discontinuity if the parameters ahead of it and its velocity are known. The dependence of the thermodynamic parameters of the medium on the time after the passage of the shock discontinuity is determined by the interaction of the medium behind the shock discontinuity with the surrounding walls and by cooling due to radiation. In the case of powerful shock waves, when dissociation and ionization effects occur behind the leading front of the discontinuity, the calculation of the time dependence of the parameters of the medium becomes more difficult because the laws of interaction of a plasma with a solid have not been studied fully enough at present. Experimental studies can play a large role in this respect, although it must be noted that the overwhelming majority of studies of the pressure behind shock waves pertain to Mach numbers of less than 10. The measurement of the pressure behind shock waves with higher Mach numbers is reported on only in [1, 2]. We note that in [1] the main results pertain to $M < 17$; the few values of the pressure obtained for high Mach numbers (about 35) lie considerably below the calculated values (by two to three times). The pressure behind incident and reflected shock waves in xenon in the range of Mach numbers of 10-20 is measured in [2] and agreement of the experimental and calculated data is noted.

Thus, there are almost no studies of the pressure behind shock waves with $M > 20$ (a few experimental values of the pressure behind incident shock waves in air, obtained in [1], are an exception), when ionization and radiant energy transfer behind the shock waves play a vital role. Therefore, the pressure behind reflected shock waves in argon up to the conditions when single ionization of the argon atoms is complete and the number of doubly ionized atoms is comparable to and may even exceed the number of singly ionized atoms was studied in the present work. A two-diaphragm shock tube, which made it possible to obtain shock-wave velocities of up to $10.5 \cdot 10^3$ m/sec in argon with an initial pressure of $1.33 \cdot 10^2$ N/m^2, was constructed and prepared for this purpose. The shock tube consists of three chambers (of low pressure, high pressure, and intermediate pressure) separated from one another by copper diaphragms $2\text{-}3 \cdot 10^{-3}$ m thick containing cuts whose depth varied from $0.5 \cdot 10^{-3}$ to $2.8 \cdot 10^{-3}$ m. All the chambers were made of stainless steel. The inner diameter of the low-pressure chamber was 0.102 m, the outer diameter 0.128 m, and the length 8 m. The inner diameter of the high-pressure and intermediate-pressure chambers was 0.1 m, the outer diameter was 0.2 m, the length of the high-pressure chamber was 2.5 m, and that of the intermediate-pressure chamber was 3 m. These chambers can be evacuated by VN-I type pumps to a pressure of $1.33 \cdot 10$ N/m^2 and the low-pressure chamber to 1.33 N/m^2. Before an experiment all the chambers are carefully wiped with flannel moistened in alcohol. A gas mixture (OHHM) consisting of ~30% of a stoichiometric mixture of hydrogen and oxygen and ~70% of helium at an initial pressure of up to $4 \cdot 10^6$ N/m^2 was used in the high-pressure chamber. A Nichrome wire, which can be heated from an alternating current source and initiate the combustion of the OHHM, is mounted at the end of the chamber. The combustion of the OHHM leads to a sharp increase in the pressure in the chamber and to rupture of the first

M. V. Lomonosov Moscow State University. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 28, No. 4, pp. 636-642, April, 1975. Original article submitted May 27, 1974.

TABLE 1

p_h, 10^5 N/m²	16	16	16	16	17	23	31,5	27	27	39	40	40	40
p_i, 10^5 N/m²	0,75	1	1,5	2,0	1,5	1,5	1,5	1,5	2	2	2	3	4
v_1, 10^3 m/sec	6,67	7,28	7,37	5,0	7,37	10,3	8,49	6,36	8,2	6,6	6,6	7,3	5,4
v_2, 10^3 m/sec	6,82	7,76	7,8	5,0	7,8	10,46	8,48	6,81	8,0	6,6	7,0	7,7	5,4
M_1	21,4	24,4	23,7	15,6	23,2	32,2	26,6	19,9	25,7	20,6	20,6	22,9	16,7
M_2	21,4	24,0	23,4	15,6	24,2	32,8	26,6	21,4	25,1	20,6	20,6	24,1	16,9

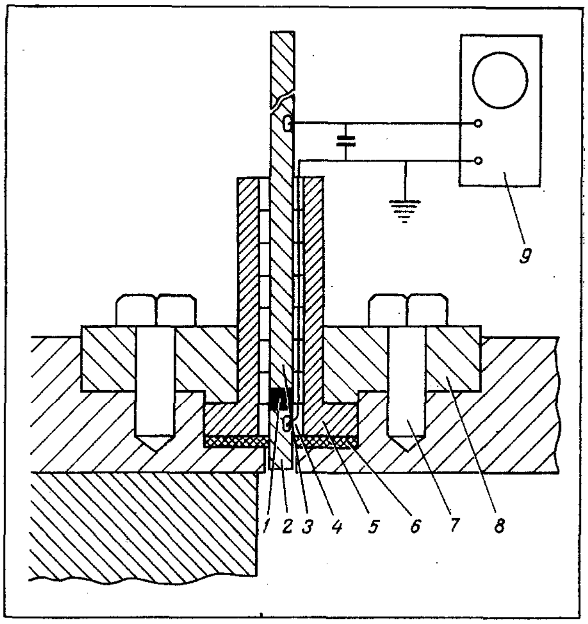

Fig. 1. Diagram of construction of piezoelectric pressure pickup: 1) piezoelectric element; 2, 3) brass rods; 4) rubber rings and epoxy resin; 5) frame of pickup; 6) Teflon ring; 7) bolt; 8) flange; 9) oscillograph.

diaphragm. After this in the intermediate chamber a shock wave is formed which reaches the second diaphragm. Before the experiment the intermediate chamber was filled with helium or hydrogen at a pressure of from several dozen atmospheres to several atmospheres.

The second diaphragm has a considerably lower strength than the first, since it is desirable that its rupture set in before the encounter of the shock wave reflected from it with the contact surface and that the helium heated by the reflected shock wave to a temperature of several thousand degrees take part in the formation of the shock wave in the low-pressure chamber. The latter circumstance leads to a considerable increase in the speed of sound in the gas behind the contact region moving in the low-pressure chamber and consequently to a considerable increase in the velocity of the shock wave propagating through the test gas in the low-pressure chamber.

The measuring sections, equipped with four ionization pickups and a pressure pickup, are mounted at the end of the low-pressure chamber. The ionization pickups are located at the following distances from the end of the shock tube: the first with respect to the movement of the shock wave at 0.925 m, the second at 0.625 m, the third at 0.485 m, and the fourth at 0.260 m. The first pickup serves to trigger the recording apparatus. The signals from the others are sent to one of the channels of a dual-beam electron oscillograph of the S-1-17 type, to the second channel of which is fed a sinusoidal signal of known frequency from a GCh-18A type generator. The velocity of the incident shock wave is determined from the time between the signals from the ionization pickups and the distance between them.

A preliminary series of experiments, in which the pressures in the high-pressure and intermediate-pressure chambers were varied with a constant pressure in the low-pressure chamber, makes it possible to establish that the highest shock-wave velocities in argon at an initial pressure of $1.33 \cdot 10^2$ N/m² are obtained when the helium pressure in the intermediate section is $1\text{-}1.5 \cdot 10^5$ N/m² with an OHHM pressure of $20\text{-}25 \cdot 10^5$ N/m². The results of this series of experiments are presented in Table 1. Further experiments showed that with a change in the initial argon pressure to $1.33 \cdot 10^3$ N/m² the optimum values of the helium and OHHM pressures have a tendency to increase slightly. It is seen from the table that the values of the shock-wave velocity in the sections between the second and third and between the third and fourth pickups do not differ from one another within the limits of the measurement errors. Hence it follows that the shock-wave velocity is constant, and therefore the measured values of the pressure were referred to this shock-wave velocity.

A diagram of the construction of the piezoelectric pressure pickup is presented in Fig. 1. The principle of operation of the pickup consists in the following: an elastic wave of deformation, produced as a result of the action of the plasma behind the shock wave on the brass rod 2, then propagates along this rod, the piezoelectric element 1, and the second brass rod 3. As a result of the deformation of the piezoelectric element a signal arises at its faces which is recorded by one of the beams of an S-1-17 type oscillograph.

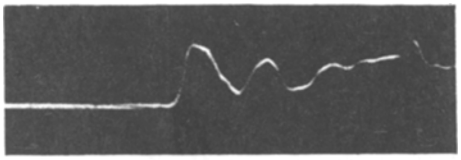

Fig. 2

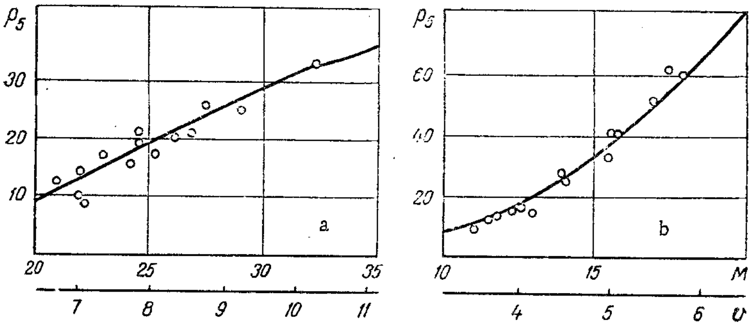

Fig. 3

Fig. 2. Oscillogram of pressure behind a reflected shock wave in argon (velocity of incident shock wave $8 \cdot 10^3$ m/sec, initial pressure $1.33 \cdot 10^2$ N/m^2).

Fig. 3. Dependence of pressure [10^5 N/m^2] behind reflected shock waves in argon on the velocity [10^3 m/sec] of the incident shock wave at an initial pressure of: a) $1.33 \cdot 10^2$ N/m^2; b) $1.33 \cdot 10^3$ N/m^2; curves: calculation of [3].

A ceramic of type TsTS-19 (diameter $5 \cdot 10^{-3}$ m, thickness $2 \cdot 10^{-3}$ m) was used as the piezoelectric element. The acoustic impedance of this ceramic is close to the impedance of brass and therefore the elastic deformation wave crosses the ceramic–brass boundary almost without reflecting, which eliminates the formation of natural oscillations of the piezoceramic. The signal can be distorted by the deformation wave reflected from the free end of the second rod, and therefore the second brass rod is made sufficiently long (0.4–0.5 m). The reflected wave returns to the piezoelectric element after $1.5\text{–}2.0 \cdot 10^{-4}$ sec. Up to this time the signal of the piezoelectric element will not be distorted if acoustical contact of the brass rods with the walls of the shock tube is absent. In order to reduce such contact to a minimum, rings 4 made of vacuum rubber are fastened to the brass rods with epoxy resin. Then the rods with the rings are placed in a metal frame and the remaining space between the rings and the frame is filled with epoxy resin. The pickup is mounted in the wall of the shock tube in such a way that the end of the first brass rod coincides with the inner surface of the shock-tube channel, and a gap of about $0.2 \cdot 10^{-3}$ m remains between the wall and the lateral surface of the rod. This gap prevents acoustical contact between the first rod and the shock-tube wall. In the presence of a contact the pressure pickup records the signal from the impact of the leaves of the rupturing diaphragm against the shock-tube wall. This signal can outstrip the shock wave or arrive almost simultaneously with it and distort the useful signal. During the passage of the shock wave by the end of the brass rod of the pickup an electrical signal arises in the rod whose origin may be connected either with electrification by friction, or with accommodation by the brass rod of free charges from the plasma, or with electromagnetic self-radiation of the plasma. Grounding of the first rod allows one to liquidate this signal distorting the pressure oscillogram. The first brass rod also allows one to avoid the effect of high heat loads on the piezoelectric element. Estimates show that when a heat flux of 10^9 W/m^2 acts for $2 \cdot 10^{-5}$ sec on a rod $5 \cdot 10^{-3}$ m in diameter and $25 \cdot 10^{-3}$ m long the mean temperature of the rod changes by about 0.2°C. The change in the temperature of the rod near the piezoelectric element will be even less.

It is preferable to calibrate the pickup under conditions close to those under which the measurements will be made. Therefore the pickup was calibrated with the help of reflected shock waves in argon at initial pressures of (25, 50, and 60) $\cdot 1.33 \cdot 10^2$ N/m^2 but at Mach numbers not exceeding 10, when ionization of the argon does not have a significant effect on its thermodynamic parameters. The velocity of a reflected shock wave in argon does not change more than twofold upon a change in the Mach number from 10 to 35, i.e., the shapes of the pressure pulses during calibration and during the pressure measurement can be assumed to be about the same. This makes it possible to exclude from consideration the amplitude–frequency characteristic of the pressure pickup. The accuracy of the pressure measurement using the pickup described is 10%.

The pressure studies were conducted behind reflected shock waves. If one considers the propagation of the incident shock wave in a coordinate system connected with the contact surface and the propagation of the reflected wave in a coordinate system connected with the end of the shock tube, and if one does not consider the effects occurring in the side wall of the shock tube and at the contact surface, then the propagation of the incident and reflected waves does not differ in principle. At the same time, the surface

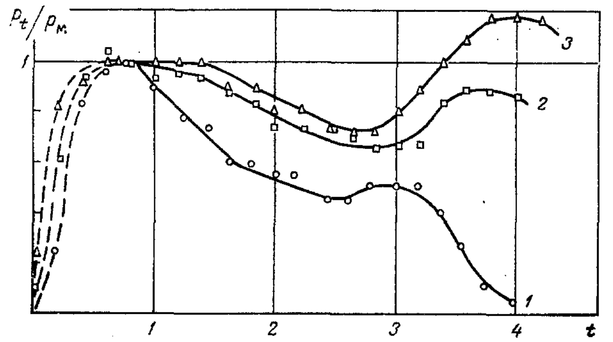

Fig. 4. Time dependence of pressure behind reflected shock waves (10^{-6} sec): 1) M = 21.4; 2) 25.0; 3) 32.8; p_0 = $1.33 \cdot 10^2$ N/m^2.

of the end of the shock tube can be considered as an ideal contact surface where the mixing or outflow of the test gas beyond the contact surface do not occur. The motion of the reflected shock wave is complicated by the region of "bifurcation" formed behind it. The role of the "bifurcation" region must be reduced to a minimum, and therefore the center of the pressure pickup was mounted at a distance of $5 \cdot 10^{-3}$ m from the end of the shock tube.

An oscillogram of the pressure pickup signal is presented in Fig. 2. The rise time of the signal is about $5 \cdot 10^{-6}$ sec. It is connected with the passage of the incident and reflected waves detected by the pickup surface. Then follows a section where the pressure remains constant within the limits of the measurement errors and then its marked decrease sets in.

The values of the pressure corresponding to the first "plateau" on the oscillogram are presented in Fig. 3. The values of the pressure calculated in [3], using the conservation laws with allowance for argon ionization, the Coulomb interaction, and lowering of the ionization potential, are given by the curves.

From a comparison of the experimental and calculated data it is seen that they agree with other each within the limits of the measurement error.

It should be noted that at shock-wave velocities of $10.5 \cdot 10^3$ m/sec (p_0 = $1.33 \cdot 10^2$ N/m^2) and $5.8 \cdot 10^3$ m/sec (p_0 = $1.33 \cdot 10^3$ N/m^2) the ratio of the energy of the Coulomb interaction to the average energy of thermal motion is 0.2 for the region behind the reflected shock wave. The agreement of the experimental and calculated pressures indicates that the corrections for the nonideal nature of the plasma in the range of temperatures and pressures studied are not large and do not essentially affect the pressure of the plasma.

The time dependences of the pressure behind reflected shock waves at an initial pressure of $1.33 \cdot 10^2$ N/m^2 for different Mach numbers of the incident shock wave are presented in Fig. 4. The ratio of the pressure at the given moment to the maximum pressure in the given experiment is laid out along the ordinate. As seen from an examination of the curves of Fig. 4, the pressure, having reached a maximum value in about $1.0\text{-}2.0 \cdot 10^{-5}$ sec, remains constant within the limits of the measurement errors, with this value, as follows from what has been said above, corresponding to the calculation for a shock discontinuity based on the conservation laws. One can also assume, according to the measurements of [4], that the temperature behind reflected shock waves in argon is also constant during approximately the same time interval.

Thus, the studies which were performed established that for about $1\text{-}2.0 \cdot 10^{-5}$ sec after the reflection of a shock wave from the end of the shock tube when $M < 35$ and the pressure is less than $6 \cdot 10^6$ N/m^2 the parameters of the argon plasma correspond to the values calculated using the conservation laws with allowance for argon ionization under the assumption that the plasma is ideal. This plasma, whose parameters are known, can be used to perform thermophysical studies.

NOTATION

p_0, p_5, p_h, p_i	are the pressures ahead of incident shock-wave front, behind reflected shock-wave front, in high-pressure chamber, and in intermediate-pressure chamber, respectively;
v_1, v_2	are the shock-wave velocities measured between second and third and between third and fourth ionization pickups, respectively;
M	is the Mach number of shock wave;
t	is the time.

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