MEASURING THE VELOCITY OF A GAS WAKE IN A SHOCK TUBE FROM THE INDUCED ELECTROMOTIVE FORCE

R. V. Vasil'eva

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ABSTRACT: It is shown that the velocity of the gas wake in a shock tube can be measured from the induced electromotive force for argon and xenon at initial pressures greater than 1 mm Hg and conductivities above 1 mho/cm. In a strongly ionized gas ($\alpha > 0.01$) the flow velocities measured directly behind the shock front are close to the flow velocities corresponding to steady-state ionization equilibrium. It is noted that the expenditure of energy to dissociate an admixture of air causes a noticeable increase in the velocity of the flow along the entire plug of hot gas. A 3-6% acceleration of the flow along the plug in the equilibrium ionization zone is observed; this is probably caused by the action of the boundary layer formed on the walls of the shock tube on the free flow.

The velocity of the wake of ionized gas behind a shock wave in argon and xenon was investigated. The flow velocity was determined from the electromotive force induced by the plasma moving through a constant transverse magnetic field [1].

The flow of ionized gas was produced in a metal shock tube with low- and high-pressure chambers 4.5 and 1 mm long, respectively, and an internal diameter of 5 cm. The initial gas pressures in the low-pressure chamber were 20, 7, and 1.3 mm Hg. The Mach number M varied from 7 to 14 for argon and from 7.5 to 18.5 for xenon.

The velocities of the wake were measured in a glass section 23 cm long, which was placed at a distance of 3.7 m from the diaphragm. A pair of copper electrodes 1 cm in diameter, flush with the walls of the tube, were placed diametrically opposite each other in the measuring section. At the ends of the measuring section were ionization probes with which the propagation velocity of the shock front was measured. In order to discover to what extent the gas flow to be studied could be considered steady, the velocity of the shock front was measured 0.7 m downstream. The propagation velocity of the shock front was constant in both gases with measurement accuracy to 2%.

Changes in the concentration of charged particles along the plug of hot gas were checked by means of a photomultiplier tube, which recorded the intensity of the continuous gas radiation in a region close to the electrodes. An ionization probe, which localized the position of the shock front, was placed in the same part of the measuring section.

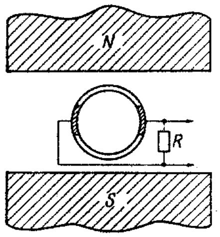


Fig. 1

The magnetic field was created by an electromagnet, which permitted variation of the magnetic induction from 0 to 7000 G. The diameter of the electromagnetic cores was 14 cm and the distance between them was 7 cm. The cross section of the measuring section and the circuit for measuring the electromotive force are shown in Fig. 1. The electromotive force induced by the plasma was determined from the voltage drop across the external load resistance R, which during the experiment was made much larger than the internal resistance of the plasma interval in any cross section of the hot plug bounded by the electrodes. The maximum value of the load resistance was 500 kohm. To register the electromotive force, the load resistance voltage was applied to the plates of an OK-17M oscillograph, whose input was made symmetric.

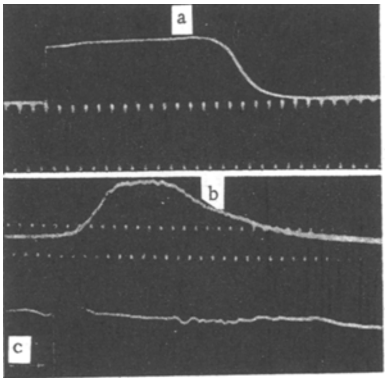


Fig. 2

The electromotive force induced when the plasma passed through the transverse magnetic field was determined from the relationship $e = uBd \times 10^{-8}$, where e is the electromotive force in volts, u is the flow velocity in cm/sec, B is the magnetic induction in gauss, and d the distance between electrodes in centimeters.

As an example, Fig. 2 shows 0 = zero oscillograms of the voltage pulse and the radiation shock-wave in argon with a Mach number $M = 10.4$ at a pressure $p_0 = 7$ mm Hg. *a* is the induced electromotive force, B = 6800 G, and the time mark is 10 μsec; and b (upper pulse) is the radiation and (lower pulse) the signal from the ionization probe localizing the shock front, and the time mark is 5 μsec.

The sharp build-up of the signal observed in the emf oscillogram corresponds to the abrupt change in the directed particle velocity directly behind the shock front. Further behind the shock front, toward the contact surface, there is an increase in emf amounting to 3-10% in different experiments. This indicates an increase in the velocity of the wake along the plug of hot gas. Behind the contact surface, the emf drops to zero, since the concentration of charged particles is equal to zero in the region of cold gas flow.

The emf build-up time as the shock front approaches the electrodes is determined by the time during which the flow of ionized gas occupies a part of the area of the electrodes, such that the internal resistance of the plasma is at least two orders smaller than the load resistance. Under the conditions of the experiment, this time turned out to be less than or equal to 1 μsec. Since the voltage taken from the load resistance was not very sensitive to changes in the concentration of charged particles, the position of the leading edge of the mixing zone in the contact region was determined from the point on the oscillogram where the pulse fell by 10% below the maximum value.

As is well known [2], the intensity of continuous radiation depends essentially on the square of the electron concentration. The length of the hot plug was measured from the radiation signal as the distance from the front to that point behind the shock front where the radiation had fallen to one-tenth the maximum value. The lengths of the hot plug measured by the two methods agreed correct to 10-15%. With different incident-flow parameters, the length of the hot plug varied from 60 to 10 cm and was one-third or one-fourth the value calculated for the ideal scheme.

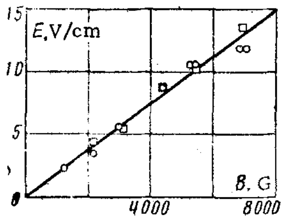


Fig. 3

The induced emf was found to be linearly dependent on the magnetic induction over the entire investigated range of Mach numbers and initial pressures, for the same incident-flow parameters and constant load resistance. This indicates that secondary reactions, such as the electrostatic effect, the flow of charges over the walls of the shock tube, etc., had no effect on the emf measurements. The velocity of the wake was determined from the slope of the straight lines representing these relationships. It is possible to determine the actual flow velocity from the formula given above only if there is a uniform distribution of velocities over the cross section of the tube, that is, if the effect of the boundary layer is small. In order to evaluate the effect of the boundary layer on the velocity profile, experiments were carried out using electrodes that protruded 1.4 cm into the tube. The electrodes were made in the form of disks with a diameter of 2.1 cm clamped in insulating holders mounted in clear plastic section.

Figure 3 shows the intensity of the induced electric field versus the magnetic induction for a shock wave in helium with $M = 1.18$ and $p_0 = 7$ mm Hg; the circles are for $d = 5$ cm; the squares for $d = 2.2$ cm. The measurements were taken at a distance of 5 cm (the length of the relaxation zone) from the shock front. As indicated by the curves, the intensity of the electric field does not depend on the distance between electrodes. One may conclude from this that with the initial gas pressures under study, the effect of the boundary layer on the velocity profile is small, and the electromotive force is apparently determined by the velocity in the flow core. However, it is necessary to note that at smaller initial gas pressures, the nonuniformity of the flow velocity over the cross section is greater due to the increase in the boundary layer and may lead to a decrease in the voltage pulse along the plug. Control experiments conducted at $p_0 = 0.7$ mm Hg and $M = 15$–19 in xenon showed that, in this case, a tendency toward a decrease in emf force with increased distance from the shock front is observed.

In addition to the effect the boundary layer has on the distribution of flow velocities over the cross section, which is significant at low Mach numbers, it also affects the internal resistance of the plasma. Experiments showed that in argon, with $M < 7$, the pulse taken from the load resistance drops along the plug toward the contact surface, irrespective of the initial gas pressure; this is probably because the internal resistance becomes comparable with the load resistance due to cold boundary layers [3].

Thus, as a result of the influence of the boundary layer, this method of measuring flow velocities from the induced emf can be considered inapplicable when the gas pressures ($p_0 < 1$ mm Hg) and conductivities ($\sigma < 1$ mho/cm) are low.

The observed increase in flow velocity behind the shock front toward the contact surface is due to the action of several processes: the expenditure of energy in ionizing the gas, the radiation yield from the volume of the hot plug, and the growth of the boundary layer, which causes acceleration of the gas in the flow core.

An increase in flow velocity in the relaxation zone is observed as a result of ionization of the gas. The time to establish equilibrium ionization in each individual experiment was determined as the rise time of the continuous radiation pulse up to the maximum value. In the oscillogram of Fig. 2b, the relaxation time is about 25 μsec in the laboratory coordinate system. It follows from Fig. 2a that the maximum velocity gradient will be in the relaxation zone of the ionization process.

At the lowest Mach numbers investigated in argon, the radiation pulse grew right up to arrival of the contact surface. At higher Mach numbers, the length of the relaxation zone amounted to no more than one-third the length of the entire hot plug and varied from 15 to 0.5 cm.

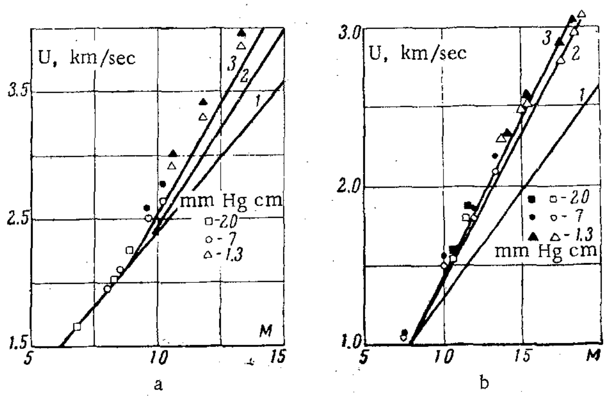
The results of measuring the velocity of the wake directly behind the shock front and at the time of establishment of ionization equilibrium at different Mach numbers and different initial pressures are shown in Fig. 4a for argon and in Fig. 4b for xenon; the clear points are velocities measured directly behind the shock front; the solid points the flow velocities at the time of equilibrium ionization; 1) calculations for $\alpha = 0$; 2) calculations for equilibrium ionization, $p_0 = 7$ mm Hg; 3) for equilibrium ionization, $p_0 = 1.3$ mm Hg.

An analysis of the experimental results shows that the flow velocities corresponding to establishment of ionization equilibrium are about 85 higher than those theoretically calculated for the same conditions, without taking viscosity into consideration.

The velocities of the wake measured directly behind the shock front coincide with the calculated values for small Mach numbers in argon. At higher Mach numbers, the flow velocities directly behind the front are considerably higher than those calculated on the assumption that in the shock front the degree of ionization $\alpha = 0$, and approach the equilibrium values of the flow velocity. This is probably because there is already considerable ionization of the gas directly behind the front in the case of strong shocks ($\alpha > 0.01$). In the case of high Mach numbers in xenon, an electrical signal at the electrodes was observed 2–3 cm before the arrival of the shock front, which indicated the presence of a noticeable concentration of charged particles in front of the wave, too [4].

This increase in flow velocities as compared with the calculated values is partially explained by the presence of air that appears in the tube as a result of leakage (0.01 mm Hg per minute). At pressures $p_0 = 1.3$ mm Hg, the air content amounts to about 3%. According to theoretical estimates, the expenditure of energy to dissociate this amount of air increases the velocity of the wake by 4–5%. Since the relaxation time of the dissociation process is short in an atmosphere of ionized gas, the increment to the flow velocity due to dissociation takes effect immediately behind the shock front and remains approximately constant along the entire plug of hot gas. Controlled experiments using small doses of air showed that the flow velocities measured directly behind the front coincide with those calculated under conditions of equilibrium dissociation and completely excited vibrational degrees of freedom.

The increase in the gas wake velocity due to radiation cooling was estimated theoretically by the scheme utilized in [2]. The calculations showed that in xenon the radiation yield introduces a noticeable correction to the flow velocity only at higher Mach values. At $M = 18$, the flow velocity at the end of the hot plug is increased by 3%. At lower Mach numbers, radiation cooling does not have any important effect on the velocity profile.



a

b

Fig. 4

The 3–6% increase in the flow velocity at the end of the hot plug after establishment of ionization equilibrium observed in the oscillograms is probably caused by the action of the boundary layer on the external flow [5, 6].

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