An Experimental and Theoretical Study of Shock-Wave Propagation through Reactive Gases under Conditions Causing a Transformation of the Flow Structure

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Abstract—Experimental observations of the transformation of the structure of shock waves entering the discharge gap of either a transverse or decaying glow discharge are presented. It is found that the total impulse of the shock wave pressure remains constant. A variation in the speed of sound, that is, the shock wave velocity, at which total dispersion of the wave occurs is found to be nonmonotonous across the discharge gap. The times over which the wave structure keeps changing after switching off the discharge have been more accurately determined. On the basis of the obtained experimental data and earlier results, a conclusion on the mechanism of this effect has been drawn. This mechanism is related to the dispersion of disturbances making up the wave structure in a relaxing medium (such as the glow discharge plasma). On the basis of a theory of this kind of dispersion, using the experimental data, and comparing energetic and temporal characteristics of the internal states of the plasma under study and the mode of sound disturbances (which according to the experiment, are responsible for the effect), we have succeeded in determining the \( O_2(a^1\Delta_g) \) state whose relaxation brings about this effect. © 2001 MAIK “Nauka/Interperiodica”.

The instability of a shock wave and the flow of an exothermically reacting gas in the wake of the wave front (combustion and dissociation) is well known [1]. At present, there is interest in studies of the instability of a shock-wave flow accompanied with endothermic reactions (dissociation and ionization). Some examples are the instability of a bow shock wave and the induced flow in polyatomic dissociating gases [2] or the instability of the shock-wave structure in a glow discharge plasma [3]. This interest is mainly caused by the possibility of reducing the drag on a body by eliminating the energy expended to increase the entropy of the shock wave. It is known that the higher the shock-wave strength, the greater this drag reduction.

Similar phenomena are observed in shock waves propagating through chemically reactive polyatomic gases [2], in ionizing shock waves [4], and in shock waves in a glow discharge plasma [3, 5, 6].

It is found that both in polyatomic gases and in the plasma, the instability is due to internal physicochemical processes. For example, the maximum in the energy spectrum of turbulent disturbances in polyatomic gases coincides with the chemical transformation energy [7]. In plasmas of the glow and decaying discharges in air, this effect also cannot be explained by the electrodynamics theory alone. Results reported in [8] show that even after the discharge has been turned off, the pressure distribution behind the shock wave remains to a considerable degree different from the classical distribution for about 100 s. In a plasma of approximately the same parameters [9], the deionization time is \( 10^{-5} \) s and the time of gas cooling is \( 10^{-4} \) s, while the deexcitation time of the vibrational states is on the order of \( 10^{-2} \) s. Thus, the common feature of all the effects considered is the fact that they are related to the physicochemical processes occurring in gases. However, their mechanisms are different. For example, the mechanism in polyatomic gases, although not thoroughly understood, has been discussed in numerous publications, which unfortunately are not well known to the general reader. This mechanism is related to the baroclinicity of the flows of chemically reactive gases, regardless of whether the energy is released or absorbed in the reactions [10]. In this case the eddy mode of the disturbances is stronger, and although the pressure perturbation is not great, it is still large enough in comparison with the pressure in front of the shock wave so as to cause a disturbance of the shock-wave front. Calculations of the amplitude and the evolution time of a disturbance at the shock-wave front for the model of a vortex possessing an energy corresponding to that of the chemical transformations [11] are in good agreement with the experimental data. Subsequent investigations of the instability of a plane-parallel flow of a chemically reactive gas in the shock layer in front of the body indicate that the flow becomes unstable with respect to high-frequency disturbances even if the transversal velocity profile has no inflection point [12], that is, not only at the flow separation point but also in front of the body in the shock layer.

So far, in a glow discharge, the transformation of the shock-wave structure has no unambiguous theoretical
There are some hypotheses concerning the shock wave [13]. However, apart from experimental data demonstrating that the effect does not depend on velocity, there are some hypotheses concerning the shock wave [13]. However, apart from experimental data demonstrating that the effect does not depend on the presence of a charged component in the gas [8], there are simple estimates made on the basis of well-known formulas of the speed of ion sound (the Mach number in the experiment is close to unity) showing that it is five times as high as the speed of sound in plasma and twice as high at the center of the discharge. Such a drastic increase of the precursor velocity is not observed in these regions, and at the center the increase in wave velocity is negligible [8].

The emergence of an ion-sound soliton due to modulation instability is also doubtful because the maximum soliton size (wavelength), as can be demonstrated, is \( l = r_D (\rho_0 / \Delta \rho)^{1/2} \approx 0.3 \text{ mm} \), where \( \rho_0 \) is the plasma density in front of the shock wave, \( \Delta \rho \) is the density jump over the shock wave, and \( r_D \) is the Debye radius. This value of the disturbance wavelength is smaller than that observed in the experiment by an order of magnitude. At larger values, the density cavity, if it exists, must collapse [14].

Ultimately, there exists a hypothesis explaining the flow transformation as caused by the energy radiated by the plasma. Radiation is characterized by dispersion, and its absorption factor depends on the wavelength. The process of energy transfer by radiation can also be described using nonlinear Korteweg–de-Vries–Burgers equations [15]. The solution of these equations, similar to the case of ion-sound waves, gives oscillations of the density and other characteristics of the flow behind the shock wave, the oscillation amplitude of small disturbances being equal to two-thirds of the wave-front amplitude. Such a behavior is not observed in experiments; more importantly, the radiation (for example, at the wavelength of excited atomic oxygen, \( =1000 \, \text{Å} \)) has an absorption factor of \( k_p = 10^{-5} \, \text{cm} \), and for this reason practically no energy absorption occurs in front of the shock wave at a distance equal to the characteristic wavelength of the initial wave (30 mm). Another model [16] describes a mechanism of fast (though not considerable) cooling of the plasma behind the shock wave due to radiation from pseudo-metastable states of atomic oxygen. It should be noted that in a number of experiments, a radiation burst in the region of unstable flow behind the shock wave was observed [17]. In [18], a kinetic mechanism was proposed which includes a number of fairly slow secondary processes (lasting about 10–100 s in the regime needed for the effect to exist). Calculations show that this kind of mechanism can provide a local pressure increase behind the shock wave of approximately 20% [16]. In the experiment, however, a much higher pressure is observed.

Thus, the mechanism of this effect has yet to be ascertained. To understand its nature, two series of experiments were carried out. One of them is a continuation of the study [8] of the time after switching off the discharge supply, during which the effect persists. The structure transformation times are derived from analysis of the Fourier series expansion of the signal. These transformation times can be compared with characteristic times of the processes involved and a process responsible for the identified instability. According to experimental results, there should be just one such process because the signal on–off time ratios are approximately unity [15]. This also means that the dominant harmonics in the Fourier expansion series of the signal are the first, the second, and perhaps two more harmonics. In the experiment, variation of the amplitudes of the harmonic with time was determined. It was easy to determine the approximate time in which the amplitudes of the two strongest harmonics dropped by an order of magnitude, \( 10^{-2} \, \text{s} \). A more accurate value, as well as other likely transformation times, can be determined as the time when the second time derivative of the dependence becomes zero, i.e., the moment when a new relationship tends to take over from the previous one. This situation can be compared to the change of acceleration sign of a body moving under the action of a system of forces while the body velocity still has not changed its direction. We have succeeded, without worsening the data accuracy, in finding all times when the second derivative becomes zero. The results in various time scales are presented in Table 1.

It is seen that as the shock-wave velocity decreases, the structure transformation time (1st harmonic) slightly increases, while for the second harmonic it does not depend on velocity. A velocity of 1.17 km/s should be noted. When the shock wave enters the test area at this velocity, the signal shape structure does not change during the first 10 ms. In Table 1, it is seen that the second harmonic of the signal undergoes changes in

<table>
<thead>
<tr>
<th>Shock wave velocity, km/s</th>
<th>( F_1'' )</th>
<th>( F_2'' )</th>
<th>( F_1'' )</th>
<th>( F_2'' )</th>
</tr>
</thead>
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<tr>
<td>1.85</td>
<td>1.0</td>
<td>13</td>
<td>3.6</td>
<td>13</td>
</tr>
<tr>
<td>1.44</td>
<td>2.3</td>
<td>–</td>
<td>3.6</td>
<td>18</td>
</tr>
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<td>18</td>
<td>–</td>
<td>13</td>
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<tr>
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<td>5.1</td>
<td>–</td>
<td>3.0</td>
<td>32</td>
</tr>
</tbody>
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Note: The 1st harmonic \( F_1 \) features a single hump and the 2nd harmonic \( F_2 \) features two humps.