Impact of shock wave on weakly ionized gas: numerical evaluation

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Considerable interest still lies with the problem of interaction of neutral and charged gas components. The research is on the interaction of strong shock waves and supersonic bodies with low-ionized plasma in this paper was presented. The attention to the problem is caused mostly by aerospace applications, but the studies are of interest also for exploring the nonlinear wave processes in the near-Earth space.

An impetus to the study of the problem was the discovery of the effect of anomalous supersonic flow of low-ionized plasma around a body [1] in the absence of energy release ahead of the body. Later, anomalous relaxation and instability of shock waves in gases [2] were found. Generation of low-ionized gas-discharge non-isothermal plasma ahead of a body, streamlined by a supersonic flow, allows lowering the intensity of a strong shock wave [3, 5]; this reduces the aerodynamic drag. The essence of the phenomenon is the formation of a region with elevated concentration of charged particles ahead of the front of a shock wave at certain speed of the latter [4, 6, 7, 8]. This critical speed is defined by the electron component temperature and ion mass. Laboratory experiments [9] have shown the flow around a body by weakly ionized air to differ markedly from that by heated neutral air. The "plasma effect" is manifested in distancing of the head shock wave from the body and lowering of its intensity. Under certain conditions, total "destruction" of a shock wave is possible due to the presence of gas ionization ahead of the body. Note that there exists an alternative way to reduce the drag: by release of energy ahead of the body in a supersonic flow [10]. It is this technique, which ignores the possible manifestation of plasma effects, that has drawn the most attention lately.

Problem statement

We study the action of a planar strong shock wave (neutral component) upon charged components of weakly ionized gas. The gas model assumes the neutral component to consist of identical molecules and the ions to be singly ionized. To reveal basic regularities, we confine ourselves to dealing with the one-dimensional stationary process. Here, all fields are dependent on single variable $\xi = x - ct$; x, t are the Cartesian coordinate and the time, $c = const$ is the speed of the front of a strong shock wave of the neutral component of three-component medium. Another restriction is imposed by the approximation of non-isothermal plasma, when the temperature of electrons is much higher than that of heavy particles. Hereinafter, indices e, i, n refer to electrons, ions, and neutral particles; T is the temperature. Limiting the examination with only the case of weak ionization allows one to neglect, at the first stage, the "reciprocal" action of the charged components upon the neutral one. Such idealization simplifies the study greatly, yet yields the field pattern, but qualitatively (rather than quantitatively) true.

Describe processes in plasma with the model of ion-acoustic approximation, $T_e \gg T_i \approx T_n$, allowing for dissipation due to elastic collisions between ions and neutral particles, and use the dynamics equations:

$$\begin{cases} \frac{\partial n_i}{\partial t} + \frac{\partial}{\partial x}(n_i v_i) = 0, \ \frac{\partial n_e}{\partial t} + \frac{\partial}{\partial x}(n_e v_e) = 0, \\ m_i \left(\frac{\partial}{\partial t} + v_i \frac{\partial}{\partial x} \right) v_i = |e|E - m_i \nu_{in}(\xi)(v_i - v_n), \\ |e|E + kT_{e0} \frac{\partial \log n_e}{\partial x} = 0, \ \varepsilon_0 \frac{\partial E}{\partial x} + |e|(n_e - n_i) = 0, \end{cases} \tag{1}$$

where n, v, m, e, E are the concentration, velocity, mass, electron charge, and the electric field, $\nu_{in}(\xi)$, k, ε_0 are the elastic collision frequency, Boltzmann constant, and vacuum permittivity.

Boundary conditions in the region of $\xi \to \infty$ are chosen from the requirement of transition of fields to the unperturbed state: $v_i = 0$, $E = 0$, $n_e = n_i = n_{e0} = n_{i0}$. Function $m_i \nu_{in} \cdot v_n$ in the motion equation for the ion component describes a stationary external source.

Reduction of the equation set to the dimensionless form

Consider stationary idealization of the problem on perturbation of the ionized component of the medium under the action of a strong shock wave of the neutral component. The source (acting force) is a strong shock wave of the neutral component (Mach number in the shock wave is much greater than one). The stationary regime corresponds to the situation, when perturbations of the charged components (electron and ion concentrations, electric field, electron and ion velocity vectors) move at speed c of the strong shock wave of the neutral component. The nonlinear set of partial differential equations (1) for stationary process reduces to a nonautonomous set of three ordinary differential equations with variable coefficient $\nu_{in}(\xi)$ for dimensionless functions and two algebraic relations:

$$\frac{d\mathbf{w}}{ds} = \mathbf{F}(\mathbf{w}, \Pi, s), \ \mathbf{w}(w_1, w_2, w_3), \ w_4 = 1 - 1/w_1, \ w_5 = 1 - 1/w_2, \tag{2}$$

where designations $s, w_1, w_2, w_3, w_4, w_5$ are introduced for dimensionless quantities: coordinate, ion and electron concentrations, electric field, ion and electron speeds. Dimensionless vector Π describes a set of three dimensionless governing parameters: $\Pi_1 = cu_s^{-1}$, $\Pi_2 = D_e \nu_0 u_s^{-1}$, $\Pi_3 = \nu_{in} \nu_0^{-1}$, where $D_e = \sqrt{\varepsilon_0 k T_0 / n_0}/e$ is the Debye radius. Parameter Π_1 is the ion-acoustic Mach number, Π_2 is the dimensionless Debye radius, Π_3 defines the dimensionless rate of collisions of ions with neutral particles, $\Pi_3 \equiv \Pi_3(s) = 1 + 2/(\gamma - 1)\,\eta(-s)$. Dimensionless functions $\mathbf{F}$ are representable as: $F_1 = -s_0 w_1^2 (w_1 w_3 - w_1/\Pi_1 + \Pi_3/\Pi_1)$, $F_2 = -s_0 \Pi_1^2 w_2 w_3$, $F_3 =$

$-s_0\,(w_2 - w_1)\,/\,(\Pi_1\Pi_2)^2$. The relationships with dimensional parameters are as follows: $w_1 = n_i n_{i0}^{-1}$, $w_2 = n_e n_{e0}^{-1}$, $w_3 = E\tilde{E}^{-1}$, $\tilde{E} = \frac{v_0 m_i c^2}{|e| u_s}$, $w_4 = v_i c^{-1}$, $w_5 = v_e c^{-1}$, $s = \xi v_0 u_s^{-1} s_0^{-1}$, where $u_s = \sqrt{(kT_{e0}/m_i)}$ is the ion-acoustic speed. Parameter u_s/v_0 is the distance traveled by the ion-acoustic wave in the ion free time. Spatial parameter s_0 is the deforming factor to be found from the existence condition for linear asymptotics (3). In region $s \to \infty$, the passage to unperturbed state (3) in set (2) occurs by exponential law. This asymptotics (3) is the boundary condition.

$$w_k \approx a_k \exp(-s)\,,\ a_k = \texttt{const},\ k = 1,\ldots,5. \tag{3}$$

Note the typical conditions of the stationary glow discharge, used to study the anomalous action of strong shock waves upon the flow around bodies in ballistic installations [2, 3, 5]: pressure 40 Thor, ion temperature $T_i \approx 1500°$ K, electron temperature $T_e \approx 12000°$ K. This corresponds to value $\Pi_2 \approx 0.13$ for the dimensionless Debye radius.

Main results and conclusions

Basing on computer-aided calculations, perturbations of weakly ionized non-isothermal gas under the action of a strong stationary shock wave of the neutral component have been studied.

An idealization of the ion-acoustic description of the plasma component was used. The effect of perturbations of the charged components upon the neutral one was neglected. The presence of two anomalous effects has been noted. At certain parameter value $\Pi_1 = \Pi_1^{cr}$, the first anomalous effect occurs - anomalous resonant (a resonance with respect to the shock wave speed) relaxation of plasma oscillations behind the front (Fig. 1). Here, total ambipolar entrainment of the charged components by a shock wave. The second anomalous effect is the resonant perturbation of ion concentration. The phenomenon essence is as follows. At certain parameter value $\Pi_1 = \Pi_1^H$, realignment of fields in the plasma precursor takes place. The maximum of ion concentration w_1 disappears, and dependence $w_1\,(s)$ becomes monotonic (Fig. 2). This is a counterpart of the hydrodynamic "Houston's horse" effect on the water surface in a narrow shallow channel.

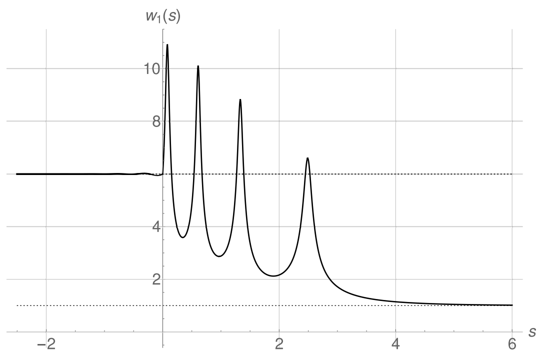

Figure 1: *Dimensionless ion density, at given parameters* $\Pi_2 = 0.2, \Pi_1 = \Pi_1^{cr} = 1.3571$. *It corresponds to the total ambipolar augmentation of charged particles by a shock wave.*

The following result can be formulated on reduction of the intensity of a strong shock wave at the stage, preceding the manifestation of the second effect. Such reduction should occur due to a specific profile of the ion concentration in the vicinity of the front (Fig. 2). Formation of profile *ABC* of ion component concentration $w_1(s)$ is possible in the vicinity of the front, when profile inflection point C with the maximum value of the ion concentration gradient is found on the front at parameter value $\Pi_1 = \Pi_1^a$. If the situation realizes, when point C is located on the front $s = 0$ (Fig. 2), the ion component should produce a force that reduces the neutral component concentration. This takes place due to positive gradient $dw_1/ds > 0$. Certainly, the magnitude of the effect is to be estimated when examining the solution of the nonstationary problem of the action of a shock wave upon weakly ionized gas. Laboratory experiment data to corroborate such influence are available [9]. In such a case, a paradoxical situation arises: low-ionized plasma (the nonperturbed state is meant) exerts effect upon the neutral component and the reduction of the shock wave intensity.

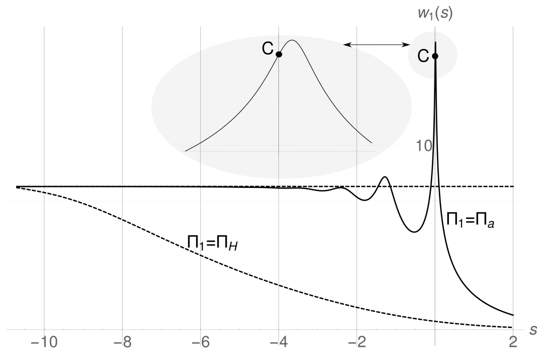

Figure 2: *The dashed line corresponds to the effect of plasma Houston's horse,* $\Pi_1^H \approx 9$. *Solid line corresponds to the max value of* $w_1'(s)$ *at the point of inflection C,* $\Pi_1^a \approx 2.32$.

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