Shock wave structure reconstruction in reacting gases

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Abstract: Instability of shock waves in plasma and reacting gases with endothermic reactions have important applications in aerodynamics due to the possibility of reduction to a great extend of aerodynamic drag of bodies. Nevertheless in the problem of turbulent mixing of compressible media this effect could be applied because the Rayleigh-Taylor instability has common base with the baroclinic mechanism of the effect. Experimental results and mechanism of this effect are discussed in this investigation

1. Introduction.

Instability of shock wave due to the exothermic reaction is well known [1]. To-day shock wave instability connected with endothermic reactions is of great interest. In a long time in different countries an influence of endothermic physical-chemical processes (dissociation, ionization) on stability and structure of shock wave flow was investigated. [2-8,13-19]. It should be noted that different four effects should be distinguished: flow instability in front of body bow in some polyatomic gases, instability of flow behind ionizing shock wave, reconstruction of moderate shock wave flow structure in plasma of glow and decay electrical discharge in argon and in air and, finally, instability of strong shock wave in gas plasma. In spite of different mechanism of them there is common quality of three first of them. It is endothermic character of reactions being behind the front of shock wave. The endothermic reactions take an important priority of exothermic ones. At endothermic reactions the body aerodynamics drag should be less in comparison with the exothermic reactions. Furthermore at exothermic reactions shock wave and flow instability takes the form of local explosions whereas at endothermic reactions instability can have the appearance of stratification of shock wave.

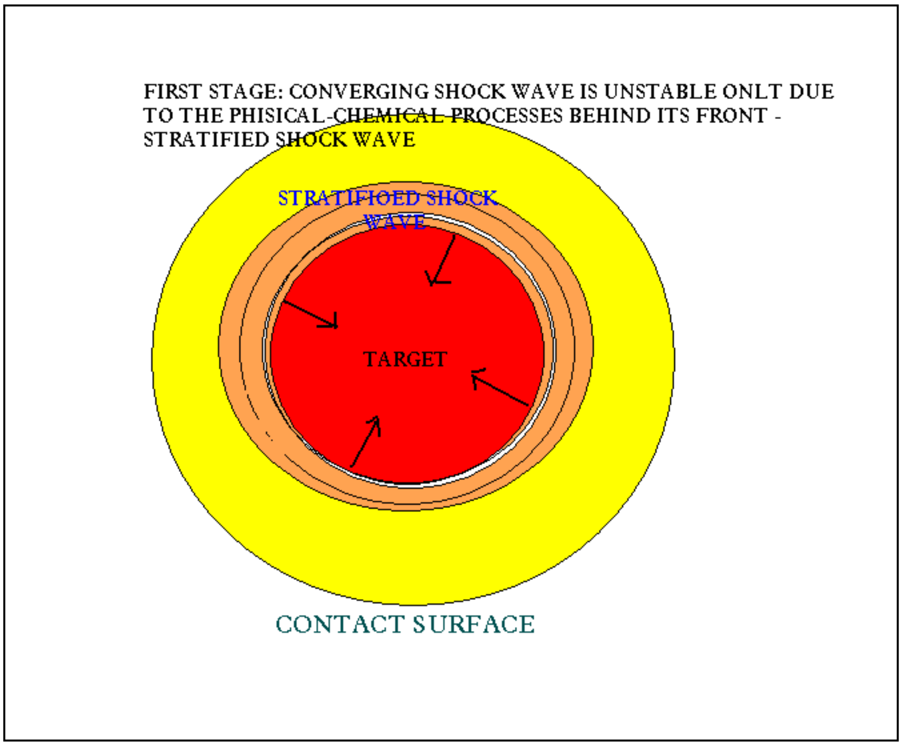

Fig.1. Sketch of the compression process.

Last property certainly is very important for target compression at the laser thermonuclear fusion since it hampers the development of heterogeneity of compressed target. At the stratification entropy increasing at shock wave is almost lacking in such manner as it would be at adiabatic compression. It would result in more intense compression without energy losses. A sketch of the compression process is shown at Fig.1. Of course, effectiveness of process stated depends on evolution time of instability effect. However, evolution time could be changed using results of the effect theory, for example, in the way of selection of the target composition. In this work some new progress in the theory of the effects will be presented, especially in the field of reconstruction of shock wave flow structure in plasma of glow and decay electrical discharge. At moderate shock waves the effect mechanism is occurred to be described in terms of equilibrium and non equilibrium, quasi stationary sound speed. As to strong shock waves it should be noted that the electrical plasma is energetic medium with the high level of inner states of excitation. The ionization potential of air and argon is very high. It is about 10 eV. It's well known that at pressure increasing degree of ionization drops very well, but at temperature increasing one is augmented. Behind shock wave both pressure and temperature are increased. But at strong shock wave pressure increasing is much great than temperature increasing particularly for plasma which has low (close to 1) ratio of specific heats – κ. The matter is that pressure increasing is proportional to $\kappa+1$ whereas temperature increasing is proportional to $\kappa-1$. That's why plasma degree of ionization behind strong shock wave in plasma drops and at recombination of plasma inner energy of plasma evolves in the form of kinetic energy of molecules or in other words as gas temperature increasing. There is a situation which analogies to situation at exothermic reactions such as explosion. The problem of instability at exothermic reactions behind the shock wave is solved with use of classic theory of shock wave instability.

2.1.Shock wave instability in reacting gases.

To-day shock wave instability connected with endothermic reactions is of great interestю Shock flow instability is observed in dissociating gases [2,6,7,13], in air weakly ionized plasma and behind the ionizing shock wave [3-6,13-16]. Experimental results were obtained not only on shock tube installations, but for bodies in free flight on ballistic installation [2]. In reacting gases the effect was observed nearly at the regimes corresponding to begin of dissociation: CCl_2F_2 (Mach number M~4), CF_4 (M~10), CO_2(M~10), O_2 (M~7) at pressures near 30 Torr (shock tube experiments carried out under the pressure p < 5 Torr) [2,6]. In ionizing gases the effect is observed to begin of ionization behind strong shock waves for Ar, He, Xe (M~20, p~ 1-25 Torr (and for some tests up to 100 Torr). Instability in reacting gases is more convenient for application of the effect, but now there are no experimental evidence of such effect in air and to-day there are no catalysts found in air. At the same time analogous effect was found in glow discharge in air and Ar for not strong shock wave for nearly the same pressures p~10-40 Torr [3-6,13,14]. Shock wave instability and rearrangement of flow behind it in reacting gases have been very well studied. It should be recognized that to-day mechanism in reacting gases is fair known. For interested effect mechanism is conditioned of baroclinicity of reacting gas flow independently of cooling or heating of gas in reactions [6,7]. As a result the vortex mode of disturbances is amplified. In spite of small value of pressure disturbance in vortex it is sufficiently large in comparison with pressure in front of shock to destroy shock wave. Computations [7,8] show that amplitude and development time of front disturbances in front of shock wave coincides with experimental ones. Further theoretical investigations of planed-parallel flow layer of compressed reacted gas in front of body indicates instability for disturbances of high frequency (f > 8 kHz) [9]. This frequency corresponds to the beginning of ultrasonic range in air (≥20 kHz). There is question about connection of baroclinic instability (the base of shock wave instability mechanism in effect at reacting polyatomic gases) and Rayleigh-Taylor instability. In this connection it should be noted that both baroclinic and Rayleigh-Taylor instabilities arise from the lack of coincidence of density and pressure gradients. However Rayleigh-Taylor instability is the limit of baroclinic instability. For it gradients do not coincide each with other although parallel yet. Nevertheless Rayleigh-Taylor instability is not consequence of baroclinic one since for it cross-product of the gradients equal to zero.

2.2.Shock wave instability in air plasma of glow discharge. Statistical methods to describe of gas mixtures with physical-chemical processes.

As was showed previously in preceding work shop [18,19] the effect for moderate shock wave in glow discharge plasma is connected exactly with wave dispersion because total gas pressure is not changed. There is only rearrangement of pressure distribution. High-frequency component of sound waves forming the shock wave goes forward forming shock wave of so called "precursor", at the same time the low-frequency part causes the relatively slowly pressure increasing behind it. Investigations of such kind dispersion were carried out as in theoretical and in experimental works [11,12]. The general equation describing such kind dispersion in reacting gases was obtained in [11]. Common analysis of this equation at the regime of resonance and results of experiment gave the consequence that exited state, relaxation of which is responsible for effect arising, is singlet state of oxygen $O_2(a^1\Delta_g)$ [18].

Among all factors affecting process instability of shock wave in plasma and rearrangement of its structure there are influence of different physical-chemical processes and, fist of all, influence of ionization and recombination processes to sound speed.

Plasma is considered enough rarefied to regard it as ideal in statistical mean. It is considered as air with high temperature, in which inner states of freedom of molecules and atoms are exited and processes of ionization and recombination take the place. On the base of analysis of reactions [10] a number of substances are selected in plasma. It is very well known that a cause which leads to the effect arising is sound speed altering in reacting plasma [18]. As known, at non vortex flows of barotropic gas the square of the sound speed a^2 is identical to the coefficient in wave equation for velocity potential φ [20].

$$\frac{\partial^2\varphi}{\partial t^2} = a^2\Delta\varphi \quad (1)$$

In gas with physical-chemical processes an expression for square of the sound speed was derived in [21]

$$a^2 = \kappa\frac{p}{\rho} \quad (2)$$

where p - pressure, ρ - density of gas and:

$$\kappa = \langle h\rangle\gamma_0\frac{\Delta_0}{\Delta}\sum_m\langle\psi_m\rangle\frac{\Delta_m}{\Delta} \quad (3)$$

$\langle h\rangle = (e+p)/n$ – average value of enthalpy per one micro particle; $\langle\psi_m\rangle = \psi_m/n$ – average values of additive collision invariants;

$$\Delta = \frac{D(e,\psi_m)}{\partial(\gamma_0,\gamma_m)} \quad (4)$$

Δ - Jacobean of transfer from extensive thermodynamic parameters e and ψ_m to conjugate intensive parameters γ_m (m=1,2,…) and $\gamma_0 = -1/k_BT$, T – gas temperature; Δ_m - is the same as Δ, but m-th column of it is changed to column $(e + p, \psi_1, \psi_2, \psi_3, \ldots)$.

In considered case together with energy the numbers of indivisible particles (ions O^+, N^+ and electrons e^-) are conserved at collisions. Accordingly system of densities of determining extensive parameters together with density of inner gas energy e includes and following parameters: ψ_1 – number of O^+, ψ_2 – number of N^+, and ψ_3 – number of electrons e^-. Determinant Δ takes the form:

$$\Delta = \begin{vmatrix} \frac{\partial e}{\partial\gamma_0} & \frac{\partial e}{\partial\gamma_1} & \frac{\partial e}{\partial\gamma_2} & \frac{\partial e}{\partial\gamma_3} \\ \frac{\partial\psi_1}{\partial\gamma_0} & \frac{\partial\psi_1}{\partial\gamma_1} & \frac{\partial\psi_1}{\partial\gamma_2} & \frac{\partial\psi_1}{\partial\gamma_3} \\ \frac{\partial\psi_2}{\partial\gamma_0} & \frac{\partial\psi_2}{\partial\gamma_1} & \frac{\partial\psi_2}{\partial\gamma_2} & \frac{\partial\psi_2}{\partial\gamma_3} \\ \frac{\partial\psi_3}{\partial\gamma_0} & \frac{\partial\psi_3}{\partial\gamma_1} & \frac{\partial\psi_3}{\partial\gamma_2} & \frac{\partial\psi_3}{\partial\gamma_3} \end{vmatrix} \quad (5)$$

At given temperature of mixture the intensive parameters γ_m are calculated from condition of conservation of indivisible particles:

$$\sum_i k_{im}n_i = \psi_m \quad (6)$$

Here k_{im} - is number of m-th atom in i-th component of mixture, and n_i – are densities of different substances in the mixture. The densities are calculated using following formula [22]:

$$n_i = Q_i\exp(\sum_m\gamma_m k_{im}) \quad (7)$$

After substitution of received from solution of (6) values of γ_1, γ_2, γ_3 in (1) and (2) temperature dependence of coefficient κ and square of sound speed can be obtained at given beginning conditions (at constant densities ψ_1, ψ_2 and ψ_3).

On the base of offered method [21, 22] a calculation of equilibrium state of ionized mixture and coefficient κ in formula (2) for the sound speed was hold in wide range of temperature (beginning from 1000°K, when only rotation states and harmonic vibration are exited, and to temperatures at which ionization and recombination processes should be counted).

As very well known exiting of additional degrees of freedom leads to decreasing of the coefficient κ. For instance, at T=1000°K value of κ is nearly 1.35. At the same time at more low temperatures, when only rotation degrees of freedom are exited, κ = 1.40. Increasing of temperature leads to further decreasing of κ, however from some temperature, when due to dissociation free atoms come into being, κ begin to increase. This increasing continues up to temperature, when gas can be considered as fully dissociated but ionization not start yet. At this stage $\kappa \approx 1.66$. With ionization process of atoms κ begin to decrease again. Such non monotonic behavior of κ is important factor determining behavior of gases with equilibrium physical-chemical processes.

On a level with equilibrium reactions non equilibrium quasi stationary ionized mixtures can be considered. In these mixtures electron temperature is much greater than temperature of other components of the mixture. It was showed that availability of electrons with great temperature have essential influence on κ, value of which is sharply drops bringing to 1.

It is very well known that if κ is equal to 1 shock wave will be unstable in accordance with the common theory of shock wave instability [23] because shock wave becomes almost isothermal and the increase of entropy is almost zero. It should be noted that in this case shock wave becomes the almost sound wave. And it is this kind of dispersion of shock wave which is demonstrated in experiments at investigated effect.

2.3.Instability of strong shock waves in plasma.

Calculation of the flow with strong shock wave in plasma can be hold in the same manner as in any other active media, for instance in explosive substance at detonation. At exothermic reaction behind front of shock wave this problem is usual for investigation of flow behind shock wave. A single difference from detonation problem is that a value of heat energy in plasma can be much less then at detonation. It is the cause that shock wave instability in plasma is not very frequent effect. There is another vital problem. It is to find the energy of heat release at reactions of plasma recombination behind shock wave. After decision of this problem it will be easy to apply known from theory instability condition [24]:

$$\left(\frac{\partial\kappa}{\partial T}\right)_p T - \left(\frac{\partial\kappa}{\partial p}\right)_T p \succ \frac{(\kappa-1)^2}{2}\left(\frac{\kappa+1}{\kappa-1}+\frac{1}{p}\right) \qquad (7)$$

Indexes p and T mean that derivatives are calculated at constant gas pressure and temperature. So it can be seen that at the low heat release there will be no shock wave instability. That’s why shock wave is very often stable in spite of recombination just behind shock wave in plasma. For instance, such situation is observed in some experimental investigations of [25]: plasma recombination is seen very well but at some regimes shock wave is unstable while at another it is stable.

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