attention and useful discussions.

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REGULAR REFLECTION OF AN OBLIQUE SHOCK IN A PLANE FLOW OF AN IDEALLY DISSOCIATING GAS IN THE PRESENCE OF A TRANSVERSE MAGNETIC FIELD

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An oblique regular reflection is considered of a plane shock wave from a rigid wall in a steady flow of a perfect, ideally dissociating gas with infinite conductivity in the presence of a magnetic field normal to the plane of flow. A flow behind the reflected shock wave is studied in the vicinity of the triple point, i.e. the point at which the curvature of the shock wave becomes different from zero.

An assumption that a first order discontinuity occurs at the triple point, is used to obtain an expression for the jump in the derivatives of the flow parameters on the streamline emerging from this point and for the jumps in the current density and vorticity.

The properties of flow at the triple point regarded as a singularity on the reflected shock wave were first studied in [1]. Short conclusions derived from the theoretical papers dealing with the subject were given in [2]. Experimental data concerning the shock wave angles at the triple point were given in [3, 4]. Comparison of the theoretical and experimental results was presented in [5, 6], and [7, 8] analyse the Mach reflection. Theoretical and experimental results concerning the magnetohydrodynamic interaction between the reflected shock wave and a homogeneous magnetic field were given in [9].

The present paper represents a generalization of [10] to the case of an ideally conducting, dissociating gas in the presence of a transverse magnetic field.

1. Statement of the problem. The following simplifying assumptions are made: (1) viscosity, diffusion and heat conductivity are all neglected; (2) the dissociating gas is assumed diatomic and each of the reacting components is assumed to be a perfect gas; (3) the gas temperature varies from 1000° to 7000° K so that only the process of dissociation is essential, the energy used on ionization and electron excitation being neglected and (4) the radiant energy losses are not taken into account.

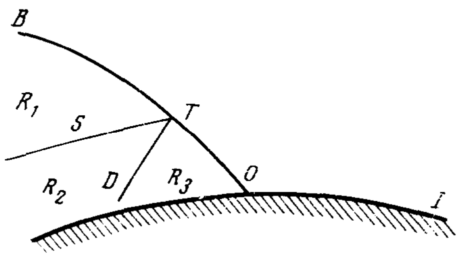

Fig. 1

The condition upstream of the incident rectilinear shock is assumed homogeneous, therefore the flow parameters in the region $IOTB$ (see Fig. 1) can be assumed constant without loss of generality. The reflected shock becomes curved behind the point T due to the effect of the sonic perturbations. The streamline ST emerging from the triple point T divides the region OTB lying behind the reflected shock wave into a region of homogeneous parameters behind the rectilinear part OT of the shock, and an inhomogeneous region (R_1) behind the curved part TB of the shock.

At the point T the curvature of the shock suffers a discontinuity, although its first derivative remains continuous, i.e. the rectilinear part of the shock is tangent to the curved part at the point T. Further it is assumed that a first order discontinuity occurs at T. Then the conditions of continuity of the total pressure (magnetic plus gasdynamic), as well as continuity of streamline curvatures, hold at this point which lies on the streamline TS. To satisfy the last condition we shall assume, following [10], that the region behind the rectilinear part of the shock wave is divided by the curved boundary (TD) into two parts: one part which is directly adjoint to the shock wave OTD (R_3), in which all parameters are homogeneous, and the region STD (R_2), in which the flow parameters vary continuously in a specific manner.

The equations of continuity, motion, energy and magnetic field induction for the case of a two-dimensional steady flow of an ideally conducting gas in the presence of a transverse magnetic field, are written in the form

$$u_i p_{,i} + \rho u_{i,i} = 0 \qquad (1.1)$$

$$\rho u_j u_{i,j} + p_{,i}{}^* = 0 \quad (p^* = p + H^2 / 8\pi) \qquad (1.2)$$

$$\rho u_i h_{,i} - u_i p_{,i} = 0 \qquad (1.3)$$

$$u_i H_{,i} + H u_{i,i} = 0 \qquad (1.4)$$

Here ρ, p, u_i and $h = h(p, \rho, \alpha)$ are, respectively, the density, pressure, velocity components and total enthalpy of the mixture (α is the degree of dissociation). The repeated index denotes summation over the region 1, 2 and a coma preceeding the index denotes differentiation with respect to the corresponding coordinate.

We shall consider the gas as a mixture formed by dissociation of a diatomic gas A_2, the molecules of which are composed of the atoms A_1 of the gas. Assuming that the dissociation is ideal we shall write, following [11], the equations of state and an expression for the enthalpy, in the form

$$p = (1+\alpha)\rho R T, \qquad h = \frac{(4+\alpha)\,p}{\rho(1+\alpha)} + \alpha D \qquad (1.5)$$

where T is temperature, R is the gas constant for A_2 and D is the energy of dissociation. In this case, using the equation of continuity for A_1 from [12], we obtain the following expression for the degree of dissociation

$$u_j \alpha_{,j} = \frac{4K_r \rho D^2 (1+\alpha)}{R^2 T_d^2}\left[\rho_d (1-\alpha)\exp\left(-\frac{T_d}{T}\right) - \rho\alpha^2\right] \qquad (1.6)$$

Here ρ_d and T_d are the characteristic density and temperature obtained in [11] and K_r is the rate of the reverse reaction. Observations show that within the temperature range given above the quantity ρ_d varies little, therefore from now on we shall assume it constant. Inserting (1.1), (1.2), (1.5) and (1.6) into (1.3), we obtain

$$u_i p_{,i} + \rho a_f^2 u_{i,i} + F = 0, \quad a_f^2 = p(4+\alpha)/3\rho \qquad (1.7)$$

$$F = \frac{4\rho K_r D^2}{3R^2 T_d^2}\left[\rho_d (1-\alpha)\exp\left(-\frac{T_d}{T}\right) - \rho\alpha^2\right]\left[\rho D (1+\alpha)^2 - 3p\right]$$

where a_f denotes the frozen speed of sound.

Let the equation of the reflected shock wave be given in the parametric form $x_i = x_i(s)$ $(i=1, 2)$, where x_i is the Cartesian coordinate of the discontinuity and s is the arc length along this discontinuity. Any streamline intersecting the reflected shock can be defined as a curve $s = \text{const}$. Let τ be the arc length along a streamline. Behind the reflected shock wave we pass to the curvilinear (s, τ)-coordinate system in such a manner, that $\tau = 0$ corresponds to the shock wave OTB (see Fig. 1). Let λ_i and n_i denote the components of the unit vector tangential and normal to the line $\tau = \text{const}$. Then we have the following relations [10]

$$\frac{\partial x_i}{\partial s} = \lambda_i, \quad \frac{\partial x_i}{\partial \tau} = \frac{u_i}{v}, \quad v^2 = u_i u_i$$

$$u_t = u_i \lambda_i, \qquad u_n = u_i n_i$$

$$n_i = e_{ij}\lambda_j \quad (e_{11} = e_{22} = 0, \quad e_{12} = -e_{21} = 1) \qquad (1.8)$$

$$f_{,i} = \frac{\partial f}{\partial s}\frac{e_{ik}u_k}{u_n} + \frac{\partial f}{\partial \tau}\frac{v n_i}{u_n}$$

Using (1.8) we now write (1.1), (1.2), (1.4) and (1.7) in the form

$$v\frac{\partial\rho}{\partial\tau}+\frac{\rho v}{u_n}n_i\frac{\partial u_i}{\partial\tau}-\frac{\rho}{u_n}e_{ij}u_j\frac{\partial u_i}{\partial s}=0 \tag{1.9}$$

$$\rho v\frac{\partial u_i}{\partial\tau}-\frac{e_{ij}u_j}{u_n}\frac{\partial p^*}{\partial s}+\frac{v}{u_n}n_i\frac{\partial p^*}{\partial\tau}=0 \tag{1.10}$$

$$\rho\frac{\partial H}{\partial\tau}=H\frac{\partial\rho}{\partial\tau} \tag{1.11}$$

$$v\frac{\partial p}{\partial\tau}-va_f^2\frac{\partial\rho}{\partial\tau}+F=0 \tag{1.12}$$

2. Properties of the flow behind the reflected shock wave.

Theorem 1. Variations in the flow characteristics along the streamlines and along the curves τ = const are connected by the following relations

$$v\,(u_n^2-a_f^{*2})\frac{\partial\rho}{\partial\tau}=\frac{\rho v}{H}\left(u_n^2-a_f^{*2}\right)\frac{\partial H}{\partial\tau}=-\rho u_ne_{ij}u_j\frac{\partial u_i}{\partial s}-F-u_t\frac{\partial p^*}{\partial s} \tag{2.1}$$

$$v\,(u_n^2-a_f^{*2})\frac{\partial p}{\partial\tau}=a_f^2\left(\rho u_ne_{ij}u_j\frac{\partial u_i}{\partial s}-u_t\frac{\partial p^*}{\partial s}\right)+F\left(\frac{H}{4\pi\rho}-u_n^2\right) \tag{2.2}$$

$$\rho v\frac{\partial u_i}{\partial\tau}=\frac{e_{ij}u_j}{\partial s}\frac{\partial p^*}{\partial s}-\frac{n_i}{u_na_f^2}\left[(v\,(a_f^*)^2\frac{\partial p}{\partial\tau}-\frac{H^2F}{4\pi\rho}\right] \tag{2.3}$$

$$(a_f^{*2}=a_f^2+H^2\,/\,4\pi\rho)$$

Proof. Multiplying (1.10) by n_i, eliminating $\partial p^*/\partial\tau$ and $n_i\partial u_i/\partial\tau$ and using (1.9), (1.11) and (1.12), we obtain (2.1). Substitution of (2.1) into (1.12) and (1.10) yields (2.2) and (2.3).

Theorem 2. The gradients of the flow characteristics along the curvilinear boundary TD are given by

$$u_{i,j}=Ln_i'n_j',\quad H_{,j}=-HLn_j'\,/\,u_n' \tag{2.4}$$

$$p_{,i}=L\left(\frac{H^2}{4\pi u_n'}-\rho u_n'\right)n_i',\qquad \rho_{,i}=-\frac{\rho Ln_i'}{u_n'} \tag{2.5}$$

$$L=\frac{F}{\rho\,[(u_n')^2-a_f^{*2}]},\qquad u_n'=u_in_i' \tag{2.6}$$

where n_i' denote the components of a unit vector normal to the curve TD.

Proof. In the region R_3 all parameters are constant, therefore at the boundary TD we have

$$u_{i,j}\lambda_j'=0,\;H_{,j}\lambda_j'=0,\;p_{,j}\lambda_j'=0,\;\rho_{,j}\lambda_j'=0 \tag{2.7}$$

$$u_{i,j}=\beta_in_j',\;H_{,i}=\xi n_j',\;\rho_{,i}=\zeta n_i' \tag{2.8}$$

Here λ_j' are the components of a unit vector tangent to DI. Multiplying (1.2) by λ_i', using (2.7) and (2.8) and taking into account the fact that $u_n'\neq 0$, we have

$$\beta_i\lambda_i'=0 \tag{2.9}$$

Eliminating $u_ip_{,i}$ from (1.2) and (1.7), and using (1.4) and (2.8), we obtain

$$u_{i,i}=\beta_in_i'=\frac{F}{\rho\,(u_n'^2-a_f^{*2})}\equiv L \tag{2.10}$$

Comparing now (2.2) with (2.10), we conclude that

$$\beta_i=Ln_i' \tag{2.11}$$

Now we use (2.8) and (2.10) to obtain from (1.4) and (1.2)

$$\xi = -HL / u_n', \quad \zeta = -\rho L / u_n'$$

which proves the theorem.

Note. When the reaction is frozen, $F = 0$ at every point of the flow. The flow in R_2 is continuous and inhomogeneous, therefore from (2.4) – (2.6) it follows that $L \neq 0$, i.e. in R_2 the following relation holds:

$$a_f^{*2} = u_n'^2$$

When $F \neq 0$, by virtue of (2.7), all quantities are continuous at the boundary and we therefore have on CD

$$a_f^{*2} \neq u_n'^2$$

Theorem 3. The quantities in the region R_1 and R_2 are connected at the point T by the following relations:

$$\frac{vu_t}{u_n}\left(\frac{\partial p^*}{\partial \tau}\right)_{R_1} - \frac{v^2}{u_n}\left(\frac{\partial p^*}{\partial s}\right)_{R_1} = -\rho u_n' u_t' L \tag{2.12}$$

$$va_f^{*2}\left(\frac{\partial \rho}{\partial \tau}\right)_{R_1} = F - \rho L u_n'^2 \tag{2.13}$$

Proof. The curvature K of the streamline is given, with (1.2) taken into account, by

$$-v^3 K = e_{ik} u_k u_j u_{i,j} = \frac{1}{\rho} e_{ij} u_k p_{,i}^*$$

From this by virtue of the continuity of the curvature of the streamline at the point T we have

$$e_{ik} u_k (p_{,i}^*)_{R_1} = e_{ik} u_k (p_{,i}^*)_{R_2}$$

Expressing the pressure gradient in R_1 in terms of the derivatives in τ and s given by (1.8) and that in R_2 using the formulas (2.4), (2.5), we obtain (2.12) at the point T Here the derivative with respect to τ of the total pressure in R_1 is determined by (2.1) and (2.2). The variation of stream parameters along the curved part of the reflected shock wave can be expressed in terms of the wave intensity, curvature of the wavefront and the parameters of the free stream. Since the total pressure varies continuously along the streamline TS, we have

$$u_i (p_{,i}^*)_{R_1} = u_i (p_{,i}^*)_{R_2} \tag{2.14}$$

Using the relations (2.4) and (2.5) to express its right-hand side at T and (1.8) for its left-hand side, we obtain

$$v\left(\frac{\partial p^*}{\partial \tau}\right)_{R_1} = -\rho L u_n'^2 \tag{2.15}$$

Replacing now the left-hand side from (1.11) and (1.12), we obtain (2.13), Q.E.D.

Theorem 4. The jumps in the values of the gradients of the flow and magnetic field parameters on the streamline TS at the point T, are given by

$$[u_{i,j}] = \frac{1}{v^2}\left\{\frac{1}{\rho u_n}\left(e_{ik}u_k - \frac{u_t}{u_n}u_i\right)\left(\frac{\partial p^*}{\partial s}\right)_{R_1} + \right.$$

$$\left. Lu_n'(n_i - n_i')\right\} u_j + \frac{1}{v^2}\left\{Lu_n' n_i - Ln_t' n_i' - \frac{v^2}{u_n}\left(\frac{\partial u_i}{\partial s}\right)_{R_1}\right\} e_{jk} u_k \tag{2.16}$$

$$[H_{,i}] = \frac{H}{v^2}\{(\rho a_f^{*2})^{-1}(F - \rho L u_n'^2) + L\} u_i +$$

$$\frac{1}{v^2}\left\{Hu_t(\rho u_n a_f^{*2})^{-1}(F - \rho L u_n'^2) - \frac{v^2}{u_n}\left(\frac{\partial H}{\partial s}\right)_{R_1} + \frac{u_t'}{u_n'} HL\right\} e_{v_j} u_j \tag{2.17}$$

$$[p,_i] = \frac{1}{v^2}\left\{\frac{L}{4\pi}(4\pi u'^2_n - H^2) - \frac{1}{a_f^{*2}}\left(\rho L u'^2_n + \frac{H^2F}{4\pi\rho}\right)\right\}u_i -$$

$$\frac{1}{v^2}\left\{\frac{v^2}{u_n}\left(\frac{\partial p}{\partial s}\right)_{R_1} + u_t(u_n a_f^{*2})^{-1}\left(\rho L u'^2_n a_f^2 + \frac{H^2F}{4\pi\rho}\right) + \frac{Lu_t}{4\pi u'_n}(H^2 - 4\pi\rho u'^2_n)\right\}e_{ij}u_j \quad (2.18)$$

$$[\rho,_i] = \frac{1}{v^2}\left\{\rho L + \frac{1}{a_f^{*2}}(F - \rho L u'^2_n)\right\}u_i + \frac{1}{v^2}\left\{u_t(u_n a_f^{*2})^{-1}(F - \rho L u'^2_n) + \right.$$

$$\left.\frac{\rho L u'_t}{u'_n} - \frac{v^2}{u_n}\left(\frac{\partial \rho}{\partial s}\right)_{R_1}\right\}e_{ij}u_j \quad (2.19)$$

Proof. Using the fact that the parameters are continuous on the streamline TS, we express the jumps in their derivatives at the point T, in the form

$$[f,_i] = [a]\,u_i + [b]\,e_{ij}u_j \quad (2.20)$$

$$[a] = \frac{1}{v^2}\{(u_i f,_i)_{R_1} - (u_i f,_i)_{R_2}\}$$

$$[b] = \frac{1}{v^2}\{(e_{ij}u_j f,_i)_{R_1} - (e_{ij}u_j f,_i)_{R_2}\}$$

Here f denotes one of the quantities u_i, H, p or ρ, and the square brackets denote the corresponding jumps at the streamline TS. Using (2.4) – (2.6) we obtain the following expressions for the region R_2 at the point T:

$$(u_j u_{i,j})_{R_2} = L u_n' n_i',\quad (e_{jk}u_k u_{i,j})_{R_2} = L u_t' n_i'$$
$$(u_i H,_i)_{R_2} = -HL,\quad (e_{ij}u_j H,_i)_{R_2} = -u_t' HL / u_n'$$
$$(u_i p,_i)_{R_2} = L\left(\frac{H^2}{4\pi} - \rho u_n'^2\right),\quad (e_{ij}u_j p,_i)_{R_2} = L u_t'\left(\frac{H^2}{4\pi} - \rho u_n'^2\right)$$
$$(u_i\rho,_i)_{R_2} = -\rho L,\quad (e_{ij}u_i\rho,_i)_{R_2} = -\rho L u_t' / u_n' \quad (2.21)$$

Further, using the coordinate transformations (1.8), expressions (2.13) and Eqs. (1.10) – (1.12), respectively, we obtain the following expressions in the region R_1:

$$(u_j u_{i,j})_{R_1} = L u'_n n_i + \frac{1}{\rho u_n} e_{ij}u_j\left(\frac{\partial p^*}{\partial s}\right)_{R_1}$$

$$(e_{jk}u_k u_{i,j})_{R_1} = -\frac{v^2}{u_n}\left(\frac{\partial u_i}{\partial s}\right)_{R_1} + \frac{u_t}{u_n}\left\{L u'_n n_i + \frac{1}{\rho u_n}e_{ij}u_j\left(\frac{\partial p^*}{\partial s}\right)_{R_1}\right\}$$

$$(u_i H,_i)_{R_1} = H(F - \rho L u'^2_n)(\rho a_f^{*2})^{-1}$$

$$(e_{ij}u_j H,_i)_{R_1} = \frac{H u_t}{\rho u_n}\frac{(F - \rho L u'^2_n)}{a_f^{*2}} - \frac{v^2}{u_n}\left(\frac{\partial H}{\partial s}\right)_{R_1} + \frac{u'_t}{u'_n}HL$$

$$(u_i p,_i)_{R_i} = -\frac{1}{a_f^{*2}}\left(\frac{H^2F}{4\pi\rho} + \rho L u'^2_n a_f^2\right)$$

$$(e_{ij}u_j p,_i)_{R_1} = -\frac{u_t}{u_n a_f^{*2}}\left(\rho L u'^2_n a_f^2 + \frac{H^2F}{4\pi\rho}\right) - \frac{v^2}{u_n}\left(\frac{\partial p}{\partial s}\right)_{R_1}$$

$$(u_i\rho,_i)_{R_1} = \frac{F - \rho L u'^2_n}{a_f^{*2}}\quad (e_{ij}u_j\rho,_i)_{R_1} = \frac{u_t(F - \rho L u'^2_n)}{u_n a_f^{*2}} - \frac{v^2}{u_n}\left(\frac{\partial \rho}{\partial s}\right)_{R_1} \quad (2.22)$$

Substituting (2.21) and (2.22) into (2.20), we obtain (2.16) – (2.19), Q.E.D.

Theorem 5. The jumps of vorticity ω and the current density j on the streamline TS at the point T are given by the formulas

$$
\begin{gathered}
[\omega] = \frac{Lu'_n}{v^2}(u_n - u_t) - \frac{1}{\rho u_n}\left\{u_i\left(\frac{\partial u_i}{\partial s}\right)_{R_1} + \left(\frac{\partial p^*}{\partial s}\right)_{R_1}\right\} \\
[J_i] = \frac{H}{4\pi v^2}\{(\rho a_f{}^{*2})^{-1}(F - \rho L u'_n{}^2) + L\} e_{ij} u_j - \\
\frac{1}{4\pi v^2}\left\{H u_t (F - \rho L u'_n{}^2)(\rho u_n a_f{}^{*2})^{-1} - \frac{v^2}{u_n}\left(\frac{\partial H}{\partial s}\right)_{R_1} + \frac{u'_t}{u'_n} HL\right\} u_i \qquad (2.23) \\
\omega = {}^1\!/_2\,(u_{j,i} - u_{i\,j})\, e_{ij}, \qquad j = e_{,j} H_{ij} / 4\pi
\end{gathered}
$$

Considering the jump of these values on the streamline TS at the point T and using the formulas (2.16) and (2.17), we obtain (2.23).

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