Study of Tangential Surfaces in Triple Shock Wave Configuration.

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1 Introduction

A shock wave impinging upon a flat surface may be reflected in different ways. It can take the form of regular or irregular reflection. At the irregular reflection configuration of three waves and tangential mixing layer arises. Tangential surfaces are unstable; they collapsed in a chain of vortices [1-7]. Real gas effect was studied in detail for the influence of the location of the three shock wave configuration and the transition from one type of configuration to another. The corrections for real gas affect drastically the relative position of shock in three shock configuration. Experimentally it was observed that this instability of tangential surfaces is more pronounced in the gas, in which physical and chemical transformations occur. In the present paper we have analytically determined the basic parameters of the mixing at the tangential surface in dependence on gas reality.

2 Mixing layers at the irregular reflection of shock waves

Let a shock wave traveling at Mach number M_0 hit a rigid surface at an angle α_0 (Fig. 1).

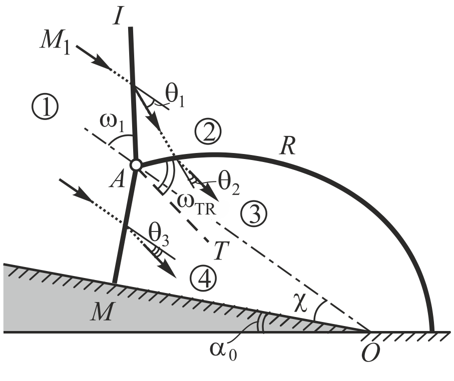

Figure 1. Scheme of irregular reflection from a flat wedge. *IA* — incident wave; *AM* — Mach wave; *AT* — tangential surface; *AR* — reflected wave. ω_1 — incidence angle ω_2 — angle of reflection.

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The entire system is self-similar with a triple point A moving at a constant angle χ to the wedge surface. From geometrical consideration it follows that relative to the triple point *A*, the approaching gas has a Mach number $M_1=M_0/\sin(\omega_1)$ where $\omega_1=90-\alpha_0-\chi$. On passing through the incident and reflected waves the gas is deflected first by the angle θ_1 and then by the angle θ_2 in the opposite direction. Applying the laws of conservation to the Mach wave the flow behind the shock wave is deflected at the angle θ_3 so the flow is directed along *AT* and θ_3 equals $\theta_1-\theta_2$.
Thus we have a surface of the mixing of two streams flowing in parallel. Pressure on both sides of the tangential surface is the same. Density, temperature, and accordingly viscosity are the different. Tangential surface, thus, can be regarded as a free surface mixing layer, the theory of which is described in [8].

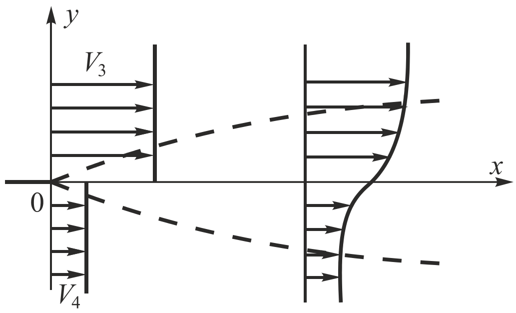

Figure 2. Transition layer between two parallel flows stating to interact at $x = 0$.

According to this theory, the velocity profile (Fig. 2) for the two parallel streams of different gases with different velocities (V_3 and V_4), densities (ρ_3 and ρ_4), and viscosities (μ_3 and μ_4) depends on two dimensionless parameters: the velocity ratio V_3/V_4 and parameter $(\rho_3\mu_3/\rho_4\mu_4)^{0.5}$. Velocity profile has an inflection point, so it rolls up in the chain of vortexes, i.e. the free mixing layer in homogenous gas shows a marked instability (Kelvin-Helmholtz).

3 Analytical calculation

In the paper the dependence of governing dimensional parameters on real gas effect is examined. In addition an angle ω_{RT} — the angle between the reflected shock wave *AR* and the tangential surface *AT*, has been determined. Calculation has been made by three shock theory [9] with the shock polars method (Fig.3). This theory can be used if in the vicinity of the triple point all three waves are straight. It is known that the calculations are in good agreement with experiment when the flow behind the reflected wave is supersonic in the system of reference connected with the triple point.

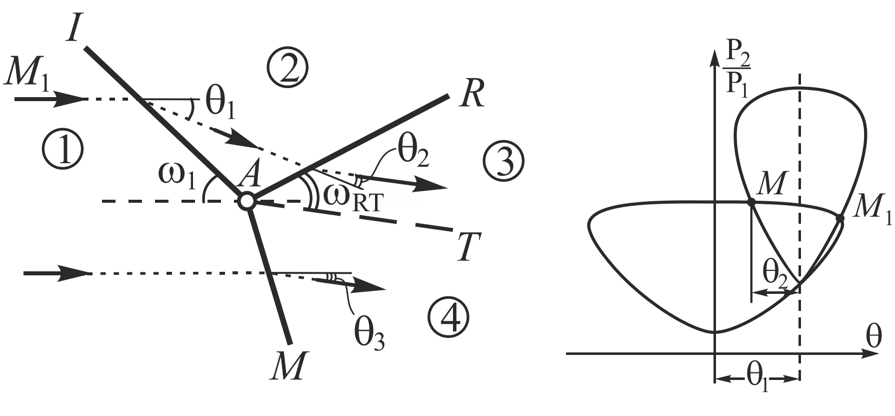

Figure 3. Left: Three shock wave configuration in the coordinate system associated with the triple point, right: shock polar.

The usual conservation laws have been used for each wave in the configuration. Where exaltation is present the enthalpy is the complicated function of gas temperature. It is convenient to introduce the effective heat capacity in order to reveal the effect of the internal degrees exaltation. One can use γ_{ef} which is determined from equation:

$$h = \frac{\gamma_{ef}}{\gamma_{ef} - 1} \cdot \frac{p}{\rho},$$

where *h, p, ρ* are enthalpy, pressure and density of the heated gas. This is only a convenient approximation and the calculations become easier.

To determine viscosity it was assumed that it depends on temperature *T* according to the following formula [4]:

$$\mu = \mu_0 \cdot \left(\frac{T}{T_0} \right)^{0.648},$$

The whole system of equations has been written about the parameters: pressure p_1, temperature T_1, the incidence angle ω_1, Mach number M_1 and the effective value of the adiabatic index γ_{ef}. Basic dimensionless parameters of the gas mixture at the tangential surface *AT* and the angle ω_{RT} have been calculated in dependence on the effective value of the adiabatic index. The calculations were made for the effective value of the adiabatic index γ_{ef}., in the range from 1.05 to 1.66. Mach number of the incoming flow M_1 in the coordinate system associated with the triple point is varied from 3 to 9, the initial temperature T_1 = 293 K. The results are presented in Figure 4 for the constant angle ω_1.

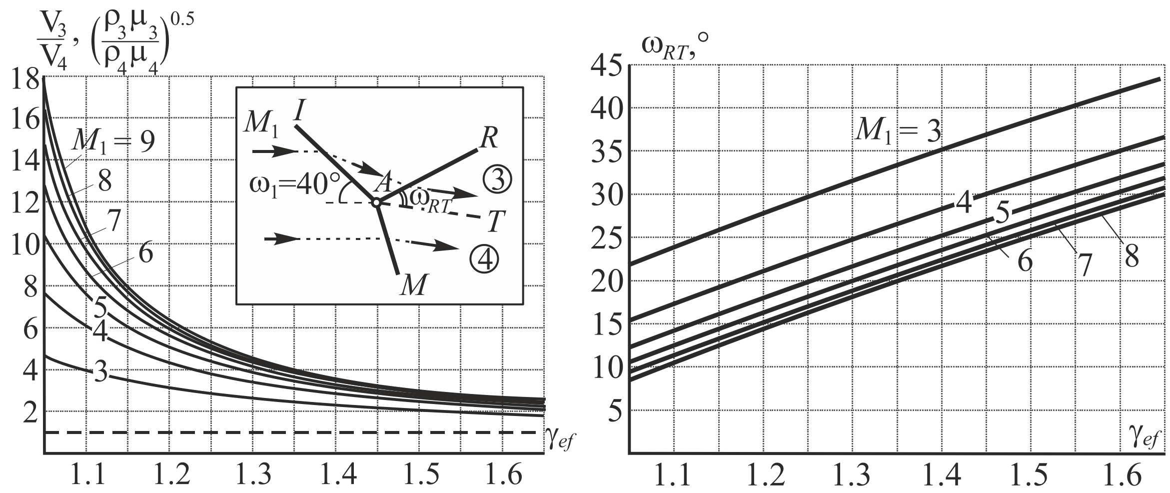

Figure 4. Dependence of the governing parameters at the contact surface on the adiabatic index γ for different Mach numbers M_1. The angle of incidence is equaled to $\omega_1 = 40° =$ const. Left: Solid line — V_3/V_4. Right: the angle ω_{RT} between the reflected wave AR and tangential surface AT .

From the calculation it is seen that in the range of investigated values of γ_{ef}, one of the defining parameters $(\rho_3\mu_3/\rho_4\mu_4)^{0.5}$ is almost unchanged and equaled near 1. The other parameter — the ratio of velocity varies very much (Figure 4, left), and in the direction of increasing with decreasing the adiabatic index. Dependence of the angle ω_{RT} on adiabatic index is also essential (Figure 4, right).

4 A new analysis of the experimental data

Earlier [1-3], it was noted that the reality of the gas has a significant effect on the behavior of the tangential surfaces. The experiments were performed in a shock tube 72 mm square. Some experiment results are shown in the Figures 5 and 6. One can see a marked difference in the type of the contact surface in nitrogen and air from that in carbon dioxide.

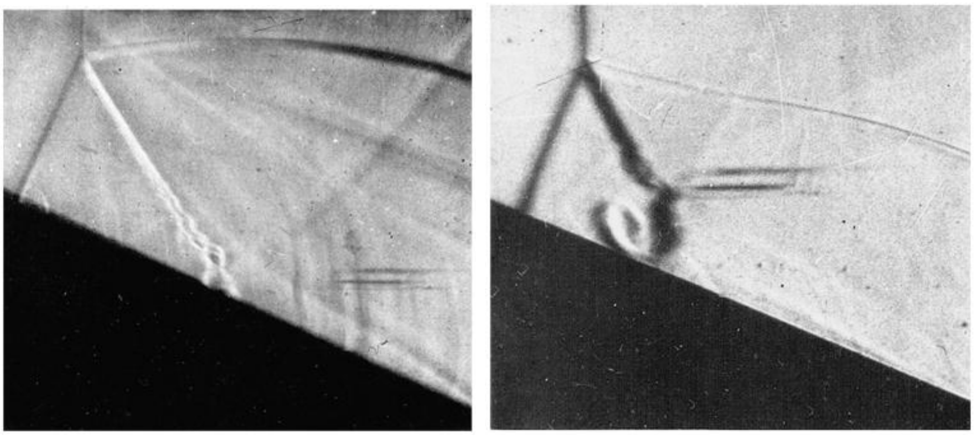

Figure 5. Schlieren pictures of shock reflection from a wedge in: Left nitrogen, α_0=24°, M_0=2.12°, p_0 =50 Torr; Right air, α_0=24°, M_0=3.55°, p_0 =12.7 torr [3]. The shock wave configuration is travelling from right to left in the absolute frame of reference.

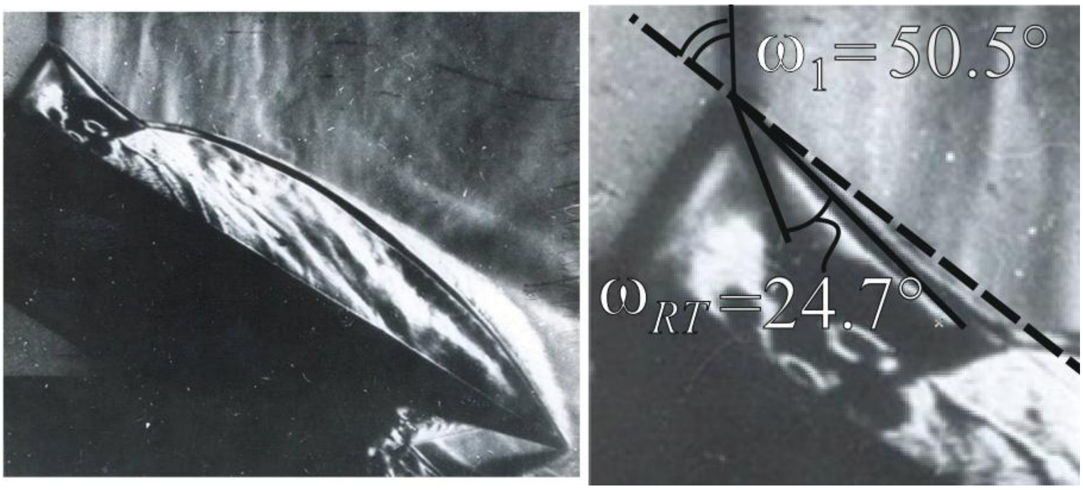

Figure 6. Schlieren pictures of shock reflection from a wedge in CO_2 gas, α_0=32°, M_0=5.18°, p_0 =20 torr [3]. The shock wave configuration is travelling from right to left in the absolute frame of reference.

It should be noted that, in the general case of strong shock waves, when physico-chemical reactions occur behind the shock wave, the self-similarity assumption does not hold true because of relaxation effects. However, in cases where either partly equilibrium or complete thermodynamic equilibrium becomes established behind the shock, self-similar solutions are in fact possible.

In order to compare the calculations with experiments a new processing of the experiments shown in Figure 6 has been done. If we consider the carbon dioxide as an ideal gas so one has taken the adiabatic index equal to 1.4, because the molecule of carbon dioxide is linear. The excitation of molecular occurs even at room temperature and certainly behind the incident and reflected waves. In addition, at the temperatures behind the incident wave carbon dioxide must dissociate. But the

relaxation times for the processes of vibration excitation and dissociation are very different. Dissociation will affect not earlier than 100 μs. after the passage of a shock wave. Vibration excitation occur faster, less than in 10 μs. Thus, in the above experiment, one can use the assumption about partly thermodynamic equilibrium, and assume that the effective value of the adiabatic index equals to 1.2 in all areas.
The results of calculation of the experiment in Figure 6 are presented in the Table 1. Two cases are given: ideal gas and vibration excitation and no dissociation.

Table 1: Results of calculation of the experiment in Figure 6

	γ_{ef}=1.4	γ_{ef}=1.21	Exp.
V_3/V_4	2.5	4.08	–
$(\rho_3\mu_3/\rho_4\mu_4)^{0.5}$	1.05	1.15	–
ω_{RT}	35.5°	24,5°	24,7°

Table 1 shows that the reality of the gas greatly affects the flow parameters. Parameter V_3/V_4 at adiabatic index equals 1.21 is 1.63 times greater than for the ideal gas with gamma=1.4. The angle ω_{RT} is approximately 11 deg less than for the ideal gas. It coincides very well with the experimental datum.

We suppose to make a new processing of a lot of earlier experiments in carbon dioxide, nitrogen and air in order to find the parameters determining the character of sleep stream in the 3 shock wave configuration. It is supposed in the future to perform numerical calculations of the behavior of the surface mixing using these experimental data.

5 Conclusions

The analytical calculation of characteristic parameters for the tangential surface in three shock wave configuration has been made. It has been shown that with a decrease in the value of the adiabatic index one of the defining parameters is almost unchanged, while the velocity ratio increases sharply with the decreasing of the adiabatic index. When reducing the adiabatic index, the angle between the tangential surface and the reflected shock wave sharply decreases. This conclusion is confirmed by the treatment of experiments conducted previously in shock tubes.
Thus it has been found that tangential surfaces are greatly influenced by the reality of the gas. These surfaces are unstable and they curl up into a chain of vortices, so the mixing process is much more efficient in gases with low adiabatic index. The study of the behavior of the contact surface is also important from the point of view of the formation of turbulence behind shock waves and therefore it may influence the deflagration detonation transition (DDT) in tubes.

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