# Interaction between Shock and Detonation Waves

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## 1. Collision of detonation waves with a shock wave

In frontal collision with a shock wave, detonation waves must discontinuously propagate into a mixture having higher temperature and density behind the shock wave. The propagation velocity as well as the mixture state is suddenly changed in such a shock collision and a cellular structure behind the detonation waves different from that before the shock collision must be observed.

We carried out some experiments of interaction between shock and detonation waves propagating in the opposite direction to each other in a stoichiometric propane-oxygen mixture in a shock tube under a room temperature of *25℃* and pressure of *37 kPa* or *40 kPa*. Measuring the propagation velocity of the both waves, some traces of the cellular structure behind the detonation waves in the collision with two different shock waves having a propagation velocity of *484 m/s* and that of *615 m/s* are recorded a soot coated plexiglas plate, while the detonation waves propagate with a velocity of *2200 m/s*.

The experimental results are shown in Table I, where $u_1$ is the propagation velocity of the colliding shock waves, $w_2$ the flow velocity behind the shock waves, $D_1$, $D_2$ the propagation velocities of the detonation waves before and after the shock collision, respectively, and $D_3$ the considered the flow velocity behind the shock waves, $M_s$, $M_{D1}$ and $M_{D3}$ are the Mach numbers of $u_1$, $D_1$ and $D_3$, respectively, $P_1$ the initial mixture pressure, $V_m$ and $T_2$ the specific volume and temperature of the, mixture behind the shock waves, respectively.

Table I

| $u_1$ (m/s) | $M_s$ | $P_1$ (kPa) | $w_2$ (m/s) | $V_m$ ($m^3$/mol) | $T_2$ (K) | $D_1$ (m/s) | $M_{D1}$ | $D_2$ (m/s) | $D_3$ (m/s) | $M_{D3}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 484 | 1.59 | 40 | 258 | $28.9\times10^{-3}$ | 375 | 2200 | 7.21 | 1990 | 2248 | 6.59 |
| 615 | 2.00 | 37 | 408 | $22.6\times10^{-3}$ | 439 | 2200 | 7.21 | 1900 | 2308 | 6.34 |

After the shock collision the propagation velocity $D_3$ of the detonation waves increases, but the Mach number decreases.

**2. Cellular structure of detonation waves** [1]

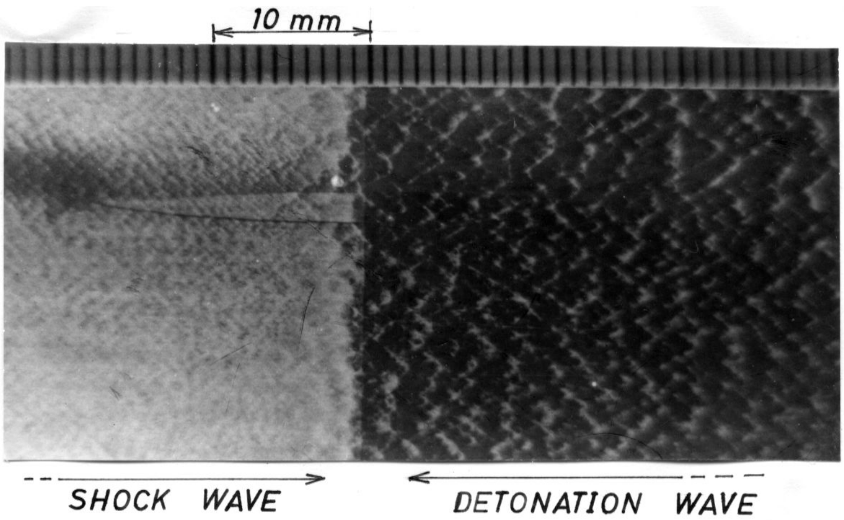


Fig. 1. Soot film trace of detonation waves at shock collision

The photograph in Fig. 1 represents an example of soot film traces at the collision of the shock and detonation waves. The cellular pattern marked by the detonation waves after the shock collision is much finer than that before the shock collision, *i.e.*, the density of apex where two lines intersect after the shock collision is much higher than that before the shock collision. As the detonation is an irreversible phenomenon, the formation of the cellular pattern must be a kind of stochastic phenomenon [2].

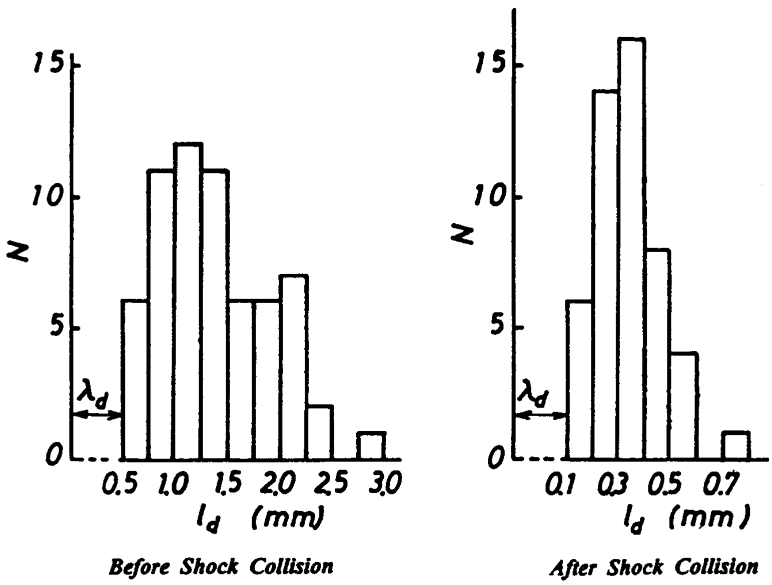


Fig. 2. Histograms of distance $l_d$ between two successive apexes

The distance $l_d$ between two successive apexes in the direction of the detonation propagation always shows some fluctuations as shown the histogram of $l_d$ in Fig. 2. Normalizing such a histogram, we can obtain a probability density $q(l_d)$ of $l_d$ in the detonation waves before and after the shock collision. From such probability densities of apex, we can further an apex formation probability $\mu_d$ $(ms^{-1} \cdot mol^{-1})$ according to the following equation [2]:

$$\mu_d = 2V_d D \cdot [lnP(0) – lnP(l)] / [F \cdot l^2], \tag{1}$$

where $V_d$ is specific volume of the mixture behind the shock waves at the detonation front, $D$ detonation propagation velocity, $P(l)=\int_l^{\infty} q(l)dl$ , $F=d_m^3$ and $d_m$ the mean planar interval between two neighboring apexes $l = l_d - \lambda_d$ and $\lambda_d$ the minimum value of $l_d$. In the next Table II all results of $\mu_d$ before and after shock collision are listed together with the state of the mixture behind the shock waves at the detonation front, as the mixture state plays the most important role for the formation of the apex , consequently the cellular pattern, where $T_d$ and $V_d$ are the temperature and specific volume of the mixture behind the shock waves at the detonation front, respectively.

Table II

| | Before shock collision | | | | | After shock collision | | | |
|---|---|---|---|---|---|---|---|---|---|
| $M_s$ | $P_1$ (kPa) | $D_1$ (m/s) | $T_d$ (K) | $V_d$ ($m^3$/mol) | $\mu_d$ ($ms^{-1} \cdot mol^{-1}$) | $D_3$ (m/s) | $T_d$ (K) | $V_d$ ($m^3$/mol) | $\mu_d$ ($ms^{-1} \cdot mol^{-1}$) |
| 1.59 | 40 | 2200 | 1700 | $6.28\times10^{-3}$ | $5.9\times10^{10}$ | 2248 | 1780 | $2.93\times10^{-3}$ | $1.9\times10^{10}$ |
| 2.00 | 37 | 2200 | 1700 | $6.80\times10^{-3}$ | $4.7\times10^{10}$ | 2308 | 1905 | $2.27\times10^{-3}$ | $3.7\times10^{10}$ |

The apex formation probability $\mu_d$ should be expressed by an equation having Arrhenius' formula as follows:

$$\mu_d = A_d \exp(- E_d / RT_d), \tag{2}$$

where $A_d$ is the frequency factor depending on the mixture ratio and density, $E_d$ the effective activation energy depending on the mixture density and components, $R$ the gas constant and $T_d$ the mixture temperature behind shock waves at the detonation front.

In Fig. 3 the relations are illustrated between $ln\mu_d$, $lnA_d$ and $E_d$ obtained in these experiments at shock collision together with those obtained in our previous experiments of the detonation waves propagating in the stoichiometric propane-oxygen mixture having lower density and different propagation velocities [2].

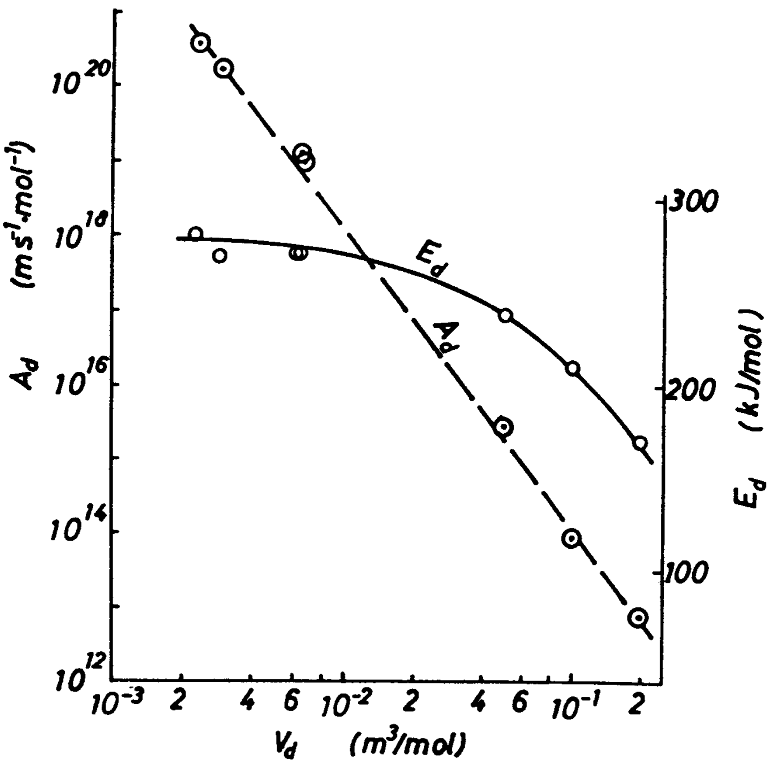


Fig. 3. Logarithm of the frequency factor $A_d$ and the effective activation energy $E_d$ at formation of cellular pattern behind detonation waves with respect to of specific volume $V_d$ behind shock waves at the detonation front.

The diagram suggests that the frequency factor $A_d$ is proportional to the fourth power of the mixture density (reciprocally proportional to the fourth power of the specific mixture volume $V_d$, while the effective activation energy $E_d$ increases with the increase of mixture density (decrease of the specific volume $V_d$), approaching a certain constant value.

**3. Conclusions**

In frontal collision with shock waves, the propagation velocity of the detonation waves increases, but its Mach number decreases. The cellular structure of the detonation waves after the shock collision becomes much finer, *i.e.*, the probability of apex formation behind detonation waves increases by the shock collision as the temperature and density of the mixture behind shock waves at the detonation front increase.

**References**


1) Shchelkin, K.I. and Troshin, Ya. K.: Gasdynamics of Combustion (Mono Book Corp., Baltimore, 1965) Chap. 1, p.18

2) Terao, K. and Azumatei, T.: Cellular pattern Formation in Detonation Waves as a Stochastic Phenomenon, Jpn. J. Appl. Phys. (1989) pp. 723-728