S. M. Kogarko, V. I. Skobelkin, and A. N. Kazakov

1958

SovietRxiv

Abstract

Full Text

Physical Chemistry

S. M. Kogarko, V. I. Skobelkin, and A. N. Kazakov

Interaction of Shock Waves with a Flame Front

(Presented by Academician V. N. Kondrat' ev, 21 VI 1958)

The problem considered is the amplification of shock waves in their interaction with a flame front due to a change in the process of normal combustion in the shock wave.

Let p_i be the pressure, ρ the density, T_i the temperature, c_i the speed of sound, and u_i the gas velocity relative to a fixed coordinate system.

In a combustible gas with parameters p_0, ρ_0, T_0, and u_0, a flame front propagates with velocity λ_0 relative to the gas particles; it transforms the combustible gas into a state with parameters p_1, ρ_1, T_1, and u_1. Toward the flame front (or following it) there travels a shock wave of amplitude $\Delta p_0 = \frac{p_0' - p_0}{p_0}$, producing behind it a gas state with parameters p_0', ρ_0', T_0', and u_i'.

Let us suppose that the length of the shock wave is sufficiently large in comparison with the reaction zone (the residence time of the reaction zone in the shock wave is greater than the reaction time). Such a shock wave interacts with the flame front as follows.

1. At the flame front, as at an interface between two media, the shock wave is rearranged. Refracted and reflected waves arise ([1]). The coefficient of refraction is determined from the condition of transition of the shock wave from a medium with parameters p_0, ρ_0, T_0 into a medium with parameters p_1, ρ_1, T_1, or conversely ([2]). In this case the flame front may approximately be regarded as a contact discontinuity.

For weak shock waves propagating from the cold gas into the hot gas, the refraction coefficient is

$$\xi_- = \frac{2}{1 + \sqrt{T_1/T_0}};$$

for waves propagating in the opposite direction,

$$\xi_+ = \frac{2\sqrt{T_1/T_0}}{1 + \sqrt{T_1/T_0}}.$$

Fig. 1

Figure 1: Fig. 1

2. In passing through the flame front, the shock wave compresses the gas in the reaction zone and raises the gas temperature in it to $T^* > T_1$. The rise of temperature in the reaction zone leads to an increase in the reaction rate, which, in turn, causes an increase in the velocity of flame propagation.

Such an increase in the velocity of flame propagation occurs rather rapidly (over a time of the order of the reaction time). Therefore the process indicated may be regarded as a certain flash in the gas flow behind the shock-wave front, leading to the formation of two additional (amplifying) shock waves propagating in opposite directions from the flame front.

The front of the shock wave moves with a subsonic velocity relative to the disturbed gas and, consequently, any disturbance in the flow behind the shock front is capable of overtaking this front and rearranging it.

The increase in the velocity of flame propagation occurs not instantaneously after the arrival of the shock wave, but after a certain relaxation time.

(time during which the reaction conditions, instantaneously changed by the shock wave, do not cause substantial changes in the diffusion and heat fluxes from the reaction zone). The relaxation time is of the same order as the reaction time [(3)].

Figure 1 schematically shows the strengthening of a shock wave as it passes through a flame front.

States 1 and 2 are formed by refraction and reflection of the shock wave at the flame front; $1'$ and $2'$ are strengthening shock waves; 0 and 3 are the initial states of the system.

Fig. 1

Using the relations at a shock front, all quantities in regions $1'$ and $2'$ can be expressed [(4)], respectively, through M_1 and M_2, where $M_1 = \frac{(v_{01})}{C_1}$ and $M_2 = \frac{(v_{02})}{C_2}$; v_{01} and v_{02} are the velocities of the gas relative to the discontinuity surfaces I and II; C_1 and C_2 are determined through the speed of sound in the combustible gas C_0.

Expressing $\Delta p_1 = \frac{p_1' - p_1}{p_1}$, $\Delta p_2 = \frac{p_2' - p_2}{p_2}$, u_1' and u_2' through M_1 and M_2, and substituting them into the equations

Fig. 2

Figure 2: Fig. 2

$$p'_1 = p'_2$$

$$u'_2 = u'_1 + \frac{(\gamma - 1)Q\lambda^*}{C_1'^2}, \tag{1}$$

which are valid at the flame front, we obtain $M_1 = M_2 = M$ and the equation with respect to M:

$$M^6 + \lambda_0 A M^5 + a_1 M^4 - a_2 A M^3 - a_3 M^2 + a_4 M + a_4 = 0, \tag{2}$$

in which all coefficients are expressed in terms of the initial parameters:

$$A = \frac{(\gamma - 1)Q}{(1 - \mu^2)C_1^3\left(1 + \frac{C_2}{C_1}\right)}; \qquad \mu^2 = \frac{\gamma - 1}{\gamma + 1};$$

$$a_1 = \frac{1 - \mu^2 - 3\mu^4}{\mu^2 + \mu^4}; \qquad a_2 = \frac{\lambda^* - \lambda_0 + 2\mu^4\lambda_0}{\mu^2 + \mu^4}$$

$$a_3 = \frac{1 + \mu^2 - 3\mu^4}{\mu^2 + \mu^4}; \qquad a_4 = \frac{1 - \mu^2}{1 + \mu^2}.$$

Fig. 2

To calculate the new flame propagation velocity λ^*, we use the Zel' dovich theory [5]:

$$\frac{\lambda^*}{\lambda_0} = \frac{T_2^*}{T_2}\sqrt{\frac{T_2 - T_0}{T_2^* - T_0}} \exp \frac{E}{2RT_2}\left(1 - \frac{T_2}{T_2^*}\right). \tag{3}$$

Here the ratio

$$\frac{T_2^*}{T_2} = \frac{1 + \Delta p_0 + (1 + \Delta p_0)^2\mu^2}{1 + \Delta p_0 + \mu^2}$$

is obtained from the Hugoniot adiabat (T_2 is the combustion temperature, E is the activation energy, R is the gas constant, Q is the heat of combustion).

It follows from (2) and (3) that the amplitude of the strengthening shock wave depends on the amplitude of the initial shock wave Δp_0, and also on the kinetic properties of the combustible mixture (reaction rate, heat capacity of the fuel, activation energy, etc.).

Figure 2 gives a plot of the dependence of the amplitude of the amplifying shock wave on the magnitude of compression in the reaction zone for two flame-propagation velocities ($\lambda_0 = 1$ m/sec and $\lambda_0 = 5$ m/sec).

The total amplification of the shock wave is determined by the relaxation process (3), which is not considered in the present article, and by the final change in the normal velocity of flame propagation in the shock wave after relaxation. For weak waves, relaxation amplification is of primary importance.

Institute of Chemical Physics
Academy of Sciences of the USSR

Received
11 VI 1958

REFERENCES

1. N. E. Kochin, *Collected Works*, 1–2, Publishing House of the Academy of Sciences of the USSR, 1949.
2. G. M. Bam-Zelikovich, *Collection: Theory of Hydraulic Dynamics*, No. 4 (1949); No. 9 (1952).
3. S. M. Kogarko, V. I. Skobelkin, DAN, 120, No. 6 (1958).
4. R. Courant, K. Friedrichs, *Supersonic Flow and Shock Waves*, IL, 1950.
5. Ya. B. Zel' dovich, ZhFKh, 14, issue 3 (1948).

Note: Figure translations are in progress. See original paper for figures.