ON SPIN DETONATION

1957

SovietRxiv

Abstract

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HYDROMECHANICS

B. V. VOITSEKHOVSKII

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(Presented by Academician M. A. Lavrent᾽ ev on 13 II 1957)

The parameters of the gas located in the interval between the shock-wave front and the combustion zone are determined by the upper point of the Hugoniot adiabat for the shock wave.

Let us agree to denote the gas located ahead of the shock-wave front by the number I, and that behind the front by the number II.

Near the line of intersection of the shock-wave front with the walls of the detonation tube, an additional rise in temperature ΔT_2 occurs owing to friction in the boundary layer. It is natural to suppose that, in gas II, a secondary detonation wave can propagate along the circumference of the cross section of the detonation tube, consisting, in turn, of a transverse shock wave and a combustion zone following the shock wave ([4]).

Gas II, adjacent to the walls of the tube, burns after secondary shock compression in the transverse shock wave. The inner part of gas II burns out owing to the closing of the turbulent-combustion front. As a result of the superposition of the translational motion of gas II with the rotational motion of the secondary detonation wave, a phenomenon arises that is called a detonation spin; in this process the brightly luminous region—the front of the secondary detonation wave—moves along a spiral.

In the calculation given below, in contrast to works ([1],[7]), it is assumed that the Jouguet condition is valid both for the entire spin detonation wave as a whole and for the secondary detonation wave moving through compressed gas II in the transverse direction along the circumference.

A diagram of the instantaneous arrangement of the fronts of the shock wave and the secondary detonation wave is shown in Fig. 1; an unwrapping onto a plane of the instantaneous position of the detonation-wave front is given. The gas flow is shown in a coordinate system connected with the established structure of the detonation wave.

Consideration of the flow around the triple point A reduces to a plane problem, since the discontinuity surfaces intersect the inner walls of the tube at right angles, and the phenomenon under study extends over a small region near the walls, small in comparison with the radius of the tube.

Fig. 1

Figure 1: Fig. 1

Figure 1 shows two possible cases of the flow of gas I around the products of the reaction of the secondary detonation wave. It is assumed that the shock-wave front AB is perpendicular to the generatrix of the detonation tube.

The angle of turning of the flow at the oblique discontinuity AE in Fig. 1*a* cannot exceed a certain critical value. An increase in the flow-turning angle above the critical value entails separation of the discontinuity AE from the point A (Fig. 1*b*). In this case a vortex may form in the neighborhood of the point A.

Let us consider in more detail the case of Fig. 1a. Gas I is compressed by the shock wave AB and passes into state II. A secondary detonation wave AC propagates through gas II. The flow in region III is described by solution (6),

$$p = p_3 \left(\cos \sqrt{\frac{\gamma - 1}{\gamma + 1}} \, \varphi \right)^{\frac{2\gamma}{\gamma - 1}} .$$

Calculation of the flow in the neighborhood of point A shows that, for most gas mixtures, the angle through which the flow is turned at the discontinuity AE must somewhat exceed the critical value.

Thus, the case most often encountered is that shown in Fig. 1b. The same applies to the gas mixture $2CO + O_2$.

Fig. 1. Development of the cylindrical surface of a detonation tube onto a plane: a –subcritical flow around the products of secondary detonation, b –supercritical flow around the products of secondary detonation; AB –shock wave; AC –secondary detonation wave; AD –contact discontinuity; AE –oblique discontinuity of the pressure field

On the basis of the physical considerations set forth above, it is not difficult to calculate the pitch of the detonation spin.

The front of the secondary detonation wave AC must be perpendicular to the streamlines as a consequence of the Jouguet condition. The normal component of the velocity of the oblique shock wave AB is equal to the spin detonation velocity D_1.

In gas II the normal component is equal to $D_1 \frac{\rho_1}{\rho_2}$; the tangential component $D_1 \tan \alpha$ is not discontinuous.

The velocity of the flow of gas II satisfies the relation

Fig. 2

Figure 2: Fig. 2

$$D_2^2 = D_1^2 \left[\left(\frac{\rho_1}{\rho_2} \right)^2 + \operatorname{ctg}^2 \alpha \right]. \tag{1}$$

ρ_1/ρ_2 and D_2 can be expressed in terms of D_1; then from relation (1) the angle α is determined, and then the pitch of the spiral, expressed in tube diameters:

$$\lambda = \pi \tan \alpha. \tag{2}$$

We write the expression for the density ratio

$$\frac{\rho_1}{\rho_2} = \frac{(\gamma+1)p_1 + (\gamma-1)p_2}{(\gamma+1)p_2 + (\gamma-1)p_1}. \tag{3}$$

Instead of p_1, p_2 we substitute their expressions in terms of C_1, D_1; neglecting small terms, we obtain

$$\frac{\rho_1}{\rho_2} = \frac{\gamma-1}{\gamma+1} + \frac{\gamma+1}{2\gamma} \left(\frac{C_1}{D_1} \right)^2. \tag{4}$$

Substituting into expression (5) for the detonation velocity of a polytropic gas (we assume $\gamma_1 = \gamma_2$)

$$D_2 = C_2 \left\{ \sqrt{\frac{\gamma^2-1}{2} \frac{Q}{C_2^2} + 1} + \sqrt{\frac{\gamma^2-1}{2} \frac{Q}{C_2^2}} \right\} \tag{5}$$

we express Q and C_2 in terms of D_1.

From equations (1), (2), (4), and (5), eliminating $\operatorname{tg} \alpha$, D_2/D_1, ρ_1/ρ_2, and neglecting small terms, we obtain

$$\frac{\pi}{\lambda} = \sqrt{ \left(\frac{1}{2} + \sqrt{\frac{1}{4} + \frac{2\gamma(\gamma-1)^2}{(\gamma+1)^2}} \right)^2 - \left(\frac{\gamma-1}{\gamma+1} \right)^2 }. \tag{6}$$

The value of λ for the gas mixture $2CO + O_2$, calculated from expression (6) at $\gamma = 1.4$, is 2.7. In work (5), for the gas mixture $2CO + O_2$, three experimental values are given, differing little from the calculated one: $\lambda = 2.95;\ 3.04;\ 3.14$.

Fig. 3

Figure 3: Fig. 3

Fig. 2. Experimental development of the cylindrical surface of a detonation tube onto a plane:
1 –assumed contour of the shock wave

In the present work, photographic recording of the detonation of the mixture $2CO + O_2$, which occurred in a vertical glass tube, was carried out through a slit opening onto the axis of the tube. It is assumed that the structure of the spin detonation wave had become established.

The photographed portion of the detonation wave crosses the slit at an angle $\alpha \simeq 45^\circ$ to the horizontal plane with velocity $D/\sin\alpha$.

The plane of rotation of the photoregister drum is inclined at an angle α to the horizontal plane, and the linear speed of the film is set so that the image of the portion of the detonation wave located in front of the slit is at rest relative to the film (3). The photographs obtained in this way (Figs. 2 and 3) show an instantaneous multiple imprint of the cylindrical surface of the luminous zone onto a plane.

Fig. 3. Experimental development of the cylindrical surface of a detonation tube onto a plane. Formation of protrusion 1 as a result of supercritical flow past detonation products

The axis of the detonation tube in Fig. 2 is directed perpendicular to the line MN. The front of the leading shock wave is not visible. It is assumed that it is located as shown in one of the periods.

From consideration of Fig. 3 it is seen that ahead of the secondary detonation wave a luminous protrusion advances, the magnitude of which varies in different periods. This protrusion is the pressure jump AE (Fig. 1b).

In some cases the size of the protrusion is greatly reduced (Fig. 2); in this case the general character of the flow becomes close to that shown in Fig. 1a, and it proves possible to measure on the photograph the angle $\gamma = 75^\circ$ between the front of the secondary detonation wave and the transverse section of the tube. The experimental value of γ is close to the calculated value $\gamma = 79^\circ$, determined from the relation $\operatorname{ctg}\gamma = \rho_1/\rho_2$.

In conclusion, it is necessary to note the substantial difference between the results presented here and the results of works (1,2,7).

1. The Hugoniot condition is satisfied both for the detonation wave as a whole and for the secondary detonation wave propagating circumferentially in the gas compressed by the shock wave.
2. The pressure at the front of the secondary detonation wave is several

times higher than in the kink of the front assumed in works ([1],[2],[7]), and is calculated as the pressure behind the front of a normal detonation wave traveling through a gas mixture of density ρ_2:

$$p_2 = \frac{\rho_2}{\gamma + 1}\left(D^2 - C_2^2\right).$$

3. Gas I flows around the rarefaction zone in the detonation products as one side of a wedge. If the angle of expansion of the products of secondary detonation exceeds the critical angle, a protrusion propagates ahead of the vertex of the front of the secondary detonation wave, arising as a result of separation of the discontinuity line from the vertex of the wedge. The occurrence of a protrusion does not follow from works ([1],[2],[7]).

In conclusion, the author expresses his deep gratitude to Academician M. A. Lavrent' ev and Academician L. I. Sedov for discussion of the results of the present work.

Moscow Institute of Physics and Technology

Received
12 II 1957

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