

THEORY OF DETONATION IN HETEROGENEOUS SYSTEMS

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In contrast to the well-studied detonation of homogeneous mixtures [1], detonation occurring in heterogeneous systems (for example, when a fuel is deposited in the form of a film on the walls of a pipe containing a gaseous oxidizer) has received little attention. Experiments have demonstrated the following characteristic properties of detonation in heterogeneous systems [2-4].

- 1) The propagation velocity of the detonation wave is a physicochemical constant of the mixture.
- 2) The structure of the detonation wave has a strictly periodic character, associated with the nonstationary mechanism of sustainment of the leading (primary) shock wave by secondary shock waves formed by the explosions that occur periodically in the detonation wave.

Whereas the first property of a heterogeneous detonation is shared by a homogeneous detonation, the second is one of its distinguishing features. The basis of the classical Chapman-Jouguet-Zel'dovich-Neumann detonation theory is the assumption that the process is one-dimensional and stationary. With respect to a heterogeneous detonation it is also of interest to formulate some ideal nonstationary detonation models. This paper describes a very simple model of a detonation of this kind, which makes it possible, in an idealized case, to take into account the energy losses caused by the essentially nonstationary character of the process.

1. We will make the usual assumptions: a) the process is one-dimensional; b) heat losses through the walls of the pipe, loss of momentum due to friction against the wall, incomplete combustion, etc., are neglected.

Let the detonation wave be situated between the sections 0-0 and 1-1. The section 0-0 corresponds to the primary shock; there are no chemical reactions beyond section 1-1. The detonation wave moves with mean velocity D .

We will consider the following detonation model. A point explosion of intensity q occurs strictly periodically (with period T) in the section 1-1. This explosion produces two secondary shock waves, one of which overtakes the primary shock, while the other moves downstream away from the detonation wave. We assume that heat release as a result of the chemical reaction occurs only in the section 1-1, while there is no reaction in the rest of the detonation wave. As a result of interaction of the primary and secondary shocks, a more powerful leading primary wave is formed whose velocity increases and then decreases to its former value, then again experiences some increase under the influence of the shock wave from the next explosion, and so on. The flow pattern in such a nonstationary detonation wave is extremely complex because interaction of the primary and secondary shocks also produces a tangential discontinuity and a weaker shock wave (or rarefaction wave) moving counter to the next secondary shock. A periodic regime is established in the detonation wave after an infinitely long time. The considered periodic flow pattern moves with some mean velocity D .

We now reverse the flow. We assume that in the new coordinate system the section 1-1 is at rest and the flow is incident on the detonation wave with velocity D . The section 0-0 will experience periodic oscillations about some mean position.

We observe the flow for a very long time $\tau (\tau \gg T)$ and assume that on the average the flow in the detonation wave is stationary in time. Then in some approximation we can write the principal laws of conservation of mass, momentum and energy in the form

$$\begin{aligned} \rho_0 D &= \rho (D - u), \quad \rho_0 D^2 - \rho (D - u)^2 = p - p_0, \\ i_0 + \frac{D^2}{2} + \frac{q}{2\rho_0 D T} &= i_1 + \frac{(D - u_1)^2}{2}. \end{aligned} \quad (1)$$

Here p , ρ , u , and i are the pressure, density, flow velocity relative to the pipe, and the heat content of unit mass of flow, respectively, averaged in time and over the cross section of the pipe. The subscript 0 corresponds to the freestream parameters and the subscript 1 to the flow parameters in the section 1-1.

The 2 in the denominator of the term with q appears because only half the heat released in the explosion is expended in the volume between the sections 0-0 and 1-1; the other half is carried downstream together with the shock waves (in the case of a point explosion the energy of the explosion is obviously distributed symmetrically relative to the site of the explosion).

We will accept the following basic hypothesis, the analogue of the Chapman-Jouguet hypothesis in stationary detonation. The mean detonation velocity relative to the mean flow velocity in the section 1-1, where explosions occur periodically, is equal to the mean local speed of sound

$$D - u_1 = a_1. \quad (2)$$

The latter hypothesis can be supported by the usual considerations of hydrodynamic stability and the detonation mechanism [1] if it is taken into account that only half the chemical energy is expended in the detonation wave and the other half is expended on the far greater mass of matter (theoretically infinitely great) situated beyond the detonation wave.

Using the system of equations (1), (2), it is possible to determine the mean detonation velocity for an ideal gas. Assuming that $i_0 \ll D^2$, as is usually the case [1], we obtain

$$D^3 = (k^2 - 1) \frac{q}{\rho_0 T} \quad (k \text{ is the ratio of specific heats}). \quad (3)$$

2. We will now discuss the proposed detonation model in relation to detonations in pipes with an oxidizer when the fuel is deposited on the walls of the pipe in a film [2-4]. In this case the following detonation wave mechanism can be visualized. The fuel is heated under the influence of the high temperature behind the shock wave; the fuel is vaporized (or possibly atomized) in the boundary layer, in which the reaction begins to proceed. The flow is accelerated to the point of turbulence, which sharply increases the rate of heat release and an explosion occurs, accompanied by total burnup in the explosion zone. If: a) the explosion zone is small in comparison with the width of the detonation wave; b) the heat released outside the explosion zone is neglected; c) incomplete combustion is neglected, it is possible to expect that the theoretical mean detonation velocity will coincide with the experimentally observed value.* We note the equation

$$q = QT D \rho_0. \quad (4)$$

Here Q is the heat per unit mass which would be released if the oxidizer and fuel were first mixed until a homogeneous mixture was obtained. If it is assumed that the reaction in the heterogeneous

*The equations cited below can also be derived if assumption b) is not made, but in its place a somewhat different detonation wave mechanism is postulated, specifically, if it is assumed that secondary detonation and retonation waves are formed during the periodically occurring explosions and all the chemical energy released is equally distributed among them.

mixture occurs precisely in the same way as in a homogeneous mixture, on the basis of (3) and (4) for the velocity of a heterogeneous detonation we obtain the simple equation

$$D = D_0 / \sqrt{2}. \quad (5)$$

where D_0 is the detonation velocity in the corresponding homogeneous mixture. For a mixture of normal hydrocarbons and oxygen the detonation velocity is 2350 m/sec for a stoichiometric composition and the maximum detonation velocity is 2650 m/sec [5]. In the corresponding case of a heterogeneous detonation the values of the theoretical velocity D are 1670 and 1870 m/sec, respectively. Heterogeneous detonation velocities of 1720 and 1850 m/sec, respectively, have been observed experimentally [3, 4].

3. The detonation model considered in para 1 is, in a certain sense, limiting. Suppose that in the detonation wave zone n identical point explosions occur. In this case it is natural to take hypothesis (2) for that section where the last explosion with respect to location in the detonation wave occurs. Using the same reasoning as before, we arrive at the following value for the detonation velocity:

$$D = \left(\frac{2n-1}{2n} \right)^{1/2} D_0. \quad (6)$$

As $n \rightarrow \infty$, this model approaches the classical model.

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REFERENCES

1. Ya. B. Zel'dovich and A. S. Kompaneets, Theory of Detonation [in Russian], Gostekhizdat, 1955.
2. R. Loison, Comp. rend., vol 243, no. 5, p. 512, 1952.
3. V. E. Gordeev, V. F. Komov, and Ya. K. Troshin, "The detonation combustion of heterogeneous systems," DAN SSSR, vol. 160, no. 4, 1965.
4. V. F. Komov and Ya. K. Troshin, "The structure and mechanism of detonation of heterogeneous systems," DAN SSSR, vol. 162, no. 3, 1965.
5. W. Jost, Explosion and Combustion Processes in Gases [Russian translation], IIL, 1952.

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