ON THE STRUCTURE AND MECHANISM OF DETONATION OF HETEROGENEOUS SYSTEMS

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ON THE STRUCTURE AND MECHANISM OF DETONATION OF HETEROGENEOUS SYSTEMS

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At the present time the detonation of homogeneous gas mixtures has been studied in considerable detail ([1,2]), but undeservedly little attention has been paid to the study of detonation of heterogeneous systems, when the fuel and oxidizer are in different aggregate states and have not been premixed. Lyoison ([3]) was the first to begin an experimental investigation of detonation in such systems and showed that detonation can propagate in a tube whose walls are coated with a layer of oil and which is filled with air. In our works ([4,5]) some regularities and limits of propagation of detonation were studied when the oxidizer was gaseous oxygen and the fuel on the tube walls consisted of the most varied petroleum oils, Vaseline, solidol, liquid individual hydrocarbons, or layers of soot. In the present work an attempt is made to approach the elucidation of the mechanism and structure of the detonation wave propagating in such heterogeneous systems.

In the experiments a tube 2 m long was used, with an internal channel of square cross section 20×20 mm. The side walls of the tube were transparent plane-parallel plates (windows) made of optical glass. At the end of the tube, or in any section of it being investigated, opposite one of the windows an IFP-200 pulsed discharge lamp was mounted; opposite the other window a photographic recorder was installed, focused on the surface of the glass farthest from it, facing into the tube. Before an experiment this surface was coated with a layer of an aqueous gelatin solution. The property of gelatin to scatter the passing light of the pulsed lamp when suddenly applied pressure acts on it was used ([6,7]). In the section of the tube under investigation, the layer of fuel was applied to the lower and upper walls. Oxygen was supplied and the process was initiated at the closed end of the tube; its other end was open to the atmosphere. Photography was carried out by the method of time sweep of the process through a longitudinal slit (2 mm wide), located either at the wall of the tube coated with a layer of fuel (Figs. $1a, 1b, 1c$), or at the tube axis (Fig. $1d$). To obtain an instantaneous photograph of the detonation wave (Fig. 2), the compensation method was used ([8]).

Figure $1a$ shows, in x (path)–t (time) coordinates, a photographic sweep of the

propagation process of a detonation wave in the heterogeneous system gaseous oxygen–solidol. In the photograph two lines are clearly visible: the leading thin, slightly sinuous one, representing the sweep of the motion of the leading shock front of the detonation wave, and following it a brightly luminous boundary–the sweep of the motion of the combustion front. The velocity of the combustion front changes periodically over wide limits. At the same time, a noticeable change also occurs in the distance between the leading front and the combustion front. In the experiment shown in the photograph, at an average detonation velocity equal to $D \simeq 1400$ m/sec, the velocity of the combustion front varied from $D_{\max} \simeq 2D$ to $D_{\min} \simeq 0.5D$, while the distances to the shock front ranged from 1 to 3 cm, respectively.

In the photographs in Figs. 1b and 1c, obtained without illumination from a pulsed lamp, inclined lines are clearly visible in the combustion zone; beyond these lines the self-luminescence of the reaction products becomes more intense. This is a streak record of the motion of secondary shock waves, during whose passage through the flame zone the velocity of the combustion front increases. In Fig. 1e the secondary shock waves propagating along the tube axis through the compressed gas are directly visible. On approaching the leading shock front the velocity of these waves decreases noticeably. The same photograph shows that the flame front near the tube axis is located at a considerably greater distance from the shock front (by a factor of 5–7) than near the tube walls, and propagates at a velocity approximately half the mean detonation velocity. At the places where secondary shock waves arise (points *m.v.* in Fig. 1e), the appearance of a detonation wave and transverse oscillations of the combustion products is usually observed. In character, the picture resembles the transition from combustion to detonation in gaseous mixtures (see, for example, Fig. 161 in work ([1]) and Fig. 5 in work ([2])), when ignition occurs inside the zone of compressed gas between the shock wave and the turbulent flame, with the sole difference that the place of origin of the secondary shock waves is always located deep within the flame zone.

It is obvious that in a heterogeneous system the cause of the formation of secondary shock waves is also local explosions (combustion pulsations) of certain volumes of the combustible mixture. In Fig. 1e two such places are visible–two combustion pulsations arising one after the other after a time $\tau \simeq 5.5 \cdot 10^{-5}$ sec, with a frequency approximately equal to 18 kHz.

An instantaneous photograph of the detonation wave is shown in Fig. 2. It can be seen from it that the shock front of the wave is curved and inclined toward the tube axis. Often, in the photographs obtained in the experiments, a complex picture is observed of the interaction of the leading front with secondary shock waves. Ignition in the detonation wave occurs at a distance approximately equal to the tube diameter, in a thin near-wall layer. As the wave advances, the flame moves only slightly away from the walls and thickens; then, at a distance of 5-7 tube diameters, it closes in the center. The combustion zone forms a well-developed elongated surface, adjoining the tube walls at its base. The flame

Figure 1

Figure 1: Figure 1

Figure 2

Figure 2: Figure 2

is strongly turbulent both as a result of the gas motion behind the curved and broken wave front and as a result of the turbulent boundary layer, whose Reynolds number at the places where the flame appears is greater than the critical value. It must be noted that additional instability of the boundary layer is created by the evaporating particles of fuel, since in parallel with combustion the processes of evaporation and mixture formation take place. The detonation complex in heterogeneous systems somewhat resembles a detonation wave in gaseous mixtures when propagating in rough tubes ([9]).

The experiments described make it possible to represent the detonation mechanism in the systems studied as follows.

The shock wave compresses, heats, and sets in motion the gas-phase oxidizer. Behind the wave front, heat exchange occurs between the heated gas and the tube wall. Owing to the low thermal diffusivity of the fuel ($a = 3 \cdot 10^{-4}$ m^2/h) and the short time intervals, the heat transferred by convection first heats the surface of the fuel layer, from which evaporation begins. After 5–20 μsec, when, apparently, a sufficient amount of fuel has evaporated and mixing of the vapors with oxygen has occurred, self-ignition of the vapor–gas mixture takes place. With the appearance of the flame, the processes of heat and mass transfer intensify. The fuel evaporates so intensely that the reaction zone separates from the walls, the flame propagates into the interior of the tube, and the thickness of the combustion zone increases. Tearing of the fuel film from the tube walls by the flow of shock-compressed gas also occurs, especially behind the secondary shock waves, which pri-

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Fig. 1

Fig. 2

leads to a significant increase in the evaporation surface. As the detonation wave advances, an excess of fuel vapor, diluted by reaction products, is created between the flame and the wall.

By turbulent pulsations, and also through the interaction of secondary shock waves with the flame [10], volumes of oxygen present in excess near the axis of the tube may be thrown into zones rich in fuel vapor. It is precisely in the regions immediately adjacent to the tube wall, at a distance of $\sim 4 \div 5$ diameters from the shock front, that the occurrence of combustion pulsations (flashes) is

observed, giving rise to secondary shock waves.

Secondary shock waves act as a mechanism that transfers energy from the reaction zone to the front, which ensures their important role in sustaining the shock front by the flame zone. During the time in which the detonation wave passes a relatively fixed cross-section of the tube, up to two secondary shock waves are formed inside the detonation complex, following one another toward the leading front. Propagating through the flame zone, they intensify the process of evaporation and mixing and increase the velocity of motion of the flame zone. Thus, at an average detonation velocity $D = 1750$ m/s (the *n*-hexadecane–oxygen system), the calculated values of the velocity, temperature, and pressure of the gas behind the secondary shock waves are, respectively, ~ 2800 m/s, $\sim 4200^{\circ}$K, and ~ 220 atm. Consequently, the fuel vapor and the flame, entering the region behind the secondary shock waves, can move at velocities exceeding the velocity of the leading shock front.

It is known [11,12] that one-dimensional detonation in gaseous mixtures is unstable with respect to changes in the distance between the shock wave and the chemical-reaction zone. Detonation in the systems studied is also unstable, since the shock wave is always detached from the combustion zone and there are causes leading to a change in the ignition delay time and to a change in the velocity of flame motion. These causes are due above all to the processes of heat and mass transfer occurring under nonstationary conditions in a substantially nonuniform state of the shock-compressed gas behind the wave front.

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