Experimental Evidence for Detonation of Lean Hydrogen-Air Mixtures Induced by Shock Focussing

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Abstract

The phenomenon of initiation of detonation in lean hydrogen-air mixtures was studied by use of shock tube with non-flat endwall. Detonation wave was induced by shock focussing at symmetric wedge reflectors with the angles 53^0 and 90^0. Two modes of detonation onset were found on the base of detail optical investigation.

Introduction

The wide diversity of the experimental facilities for study of gaseous detonations all over the world reflects complicated nature of this explosion phenomenon. The problem of adequate choice of initiator and setup scale as well as initial conditions (like pressure and temperature) is an inherent for all the studies of detonation. This is particularly important for the case of system with low detonability such as lean hydrogen-air mixture. Ciccarelli et al [1] have demonstrated that the increase of the initial temperature up to 650 K facilitates significantly the onset of detonation even in hydrogen - air mixtures of (7-8%)H_2 vol., i.e. closely to the lower flammability limit. Each test of [1] seems to be unique by itself due to the complicated procedure of direct heating of the detonation channel.

Shock tube presents another tool that enables to achieve the wide range of temperature levels in the combustible mixture to be studied. It is well known that in the case of conventional shock tube geometry the proper detonation regime arises under certain conditions just after the reflection of incident shock at the plain endwall. Obviously, in this case the reflected shock wave serves as the initiator of detonation wave. The last one propagates in the mixture prepared (i.e. compressed and heated) by the incident shock wave. The weakness of this method is that important parameters, namely the intensity of both reflected and incident shock waves, depend on the Mach number of the incident shock (M). This sets limits on the possibility of variation of the pressure and especially temperature in the mixture under investigation. Nevertheless, as it was shown in [2] (by example of sensitive hydrogen-oxygen mixtures), the substitution of the wedge reflector for the plane endwall gives rise to detonation onset in a wide range of the values M. In this case the high temperature regions arising due to the shock focussing are responsible for the ignition. The most attractive feature is that the parameters of the focussing can be controlled by not only the value of Mach number but also the reflector's shape. The present work concerns shock tube study of detonation of lean H_2-air mixtures induced by the shock focussing.

Experimental

The experiments have been carried out in a helium-driven shock tube of 54 mm x 54 mm in cross-section. The lengths of high and low pressure sections were respectively 3.15 and 6.25 m. The end flange of the low pressure section (LPS) was designed properly to allow the attachment of symmetric two-dimensional wedge reflector with the angle 53^0 (C_53) or 90^0 (C_90). The reflector's cavity was accessible to observation through glass windows mounted at the sidewalls. Before the test LPS was filled with proper hydrogen-air mixture prepared by partial pressures technique. The concentration of hydrogen in air was varied in the range (7 – 15%) H_2 vol. The range of initial pressures in the LPS was p_0 = 0.16 – 0.3 bar. The calculation of incident shock Mach number M follows the conventional method based on the pressure registration by piezoelectric gauges (Kystler 603B type) placed along the LPS. The parameter M was ranged between M = 2.3 and M = 2.9. The focussing phenomena as well as the onset and spreading of detonation were observed using multiframes laser-schlieren photography.

The experiments show that the phenomenon of detonation onset is sensitive to a set of different parameters involved in the test procedure. Figure 1 illustrates typical events accompanying the shock focussing in lean H_2-air mixtures. As it can be seen from Fig.1a, the complicated shocks configurations arising just after the penetration of shock wave into reflector's cavity do not cause even combustion process (frames 1 – 3). Detonation wave appears immediately at the apex of the reflector. This mode of the detonation onset is observed at sufficiently high values of Mach number of the incident shock. It can be referred to as a direct initiation (DI). The decrease of the parameter M leads to the shift of the location of detonation onset in the outward direction from the reflector apex. This phenomenon is illustrated by Figs.1b,c. In spite of different reflector shape and mixture sensitivity, both Fig.1b and Fig.1c show that the collision of the reflected shock with the oblique waves (frame 5 in Fig.1b and 4 in Fig.1c) gives rise to the ignition outside the reflector. The combustion zone spreads rapidly over the whole cross-section of the tube, the reaction front couples with the front of the reflected wave, thereby resulting in the formation of detonation wave. The described mode will be referred to as a transient initiation (TI).

The geometry of all the available hot spots induced by the shock focussing is evident from Fig.1d where the case of unsuccessful initiation of detonation is presented. Comparing with Fig.1c, one can note that at lower strength of the incident shock the combustion zones are spreading throughout the unburned mixture more slowly and do not influence significantly on the wave pattern. This mode of combustion is similar in appearance to that known as mild ignition (MI).

Discussion

The described tests demonstrate the performance of shock tube facility for study of detonations under elevated temperature (pressure) conditions. This seems to be the most important for the further insight into the problem of DDT in lean hydrogen-air mixtures. However, let us recall here that induced detonation wave propagates in the mixture prepared by the incident shock, i.e. in the high-speed flow. So the uncertainties due to the presence of turbulence and boundary layer must not be ruled out. For better understanding of the applicability of the shock tube technique one can compare the obtained results with the available experimental data concerning detonation of lean hydrogen-air mixtures. Figure 2 shows the temperature-concentration diagram of the outcomes of the tests devoted to initiation of detonation under shock focussing conditions. The temperature was calculated using the measured intensity of the incident shock. Also presented here are the data [1,3]. Since the tests [1,3] give only two temperature levels (500 and 650 K), the boundary *detonation-no detonation* should be considered as a first approximation.

As it is seen from Fig.2, the data obtained in shock tube experiments fall in the range of higher temperatures than the latter reported in [1,3]. Obviously, this discrepancy can be due to different scaling of the setups (in [1] and [3] the tube diameter was 27.3 and 10 cm respectively). Another reason lies in the different predetonation lengths. We have concentrated on the short distances, i.e. of the order of the reflector size, while in the facilities [1,3] the observed DDT lengths were much higher. Nevertheless, it is reasonable to suppose that realization of shock tube technique in combination with focussing test in larger scale experimental facility opens a way to elucidate the phenomena involved in DDT processes.

Acknowledgment

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References

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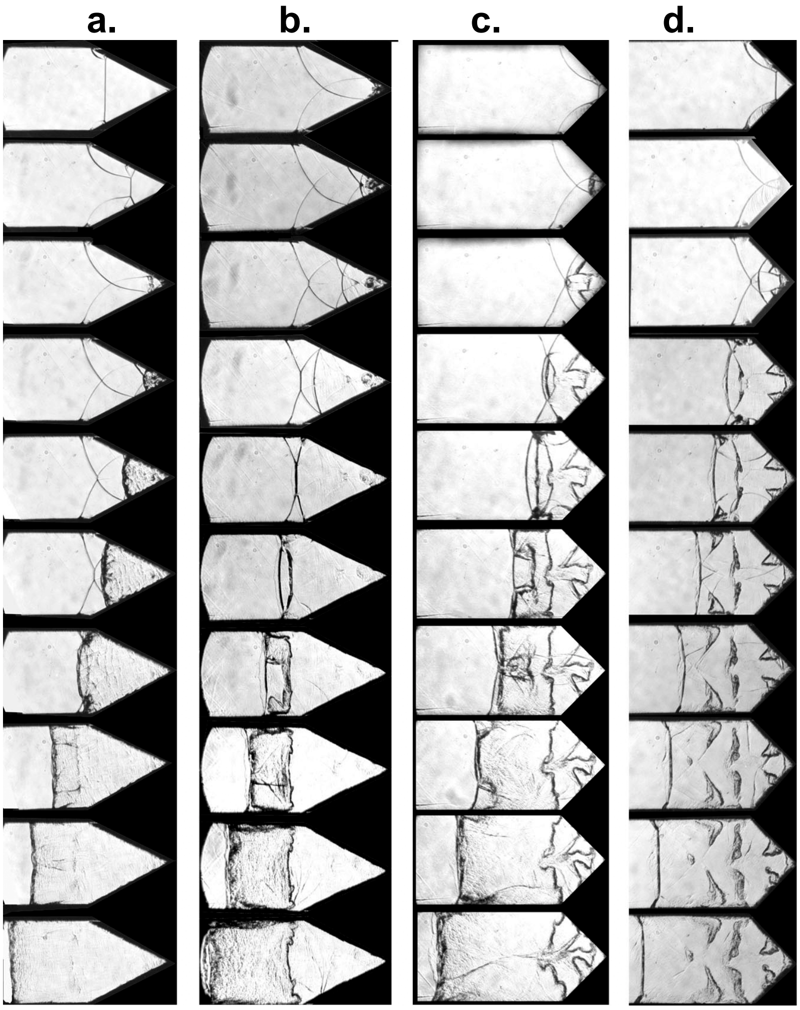

Fig. 1 Schlieren images of different ignition modes appearing in hydrogen-air mixtures under the conditions of shock focussing

a. Direct initiation: 8%H_2 in air, C_53, $M = 2.70$, $p_0 = 0.24$ bar (time between frames 20 μs)

b. Transient initiation: 8%H_2 in air, C_53, $M = 2.64$, $p_0 = 0.23$ bar (time between frames 20 μs)

c. Transient initiation: 7%H_2 in air, C_90, $M = 2.79$, $p_0 = 0.24$ bar (time between frames 20 μs)

d. Mild ignition: 7%H_2 in air, C_90, $M = 2.70$, $p_0 = 0.23$ bar (time between frames 20 μs, between frames 3 and 4 – 60 μs).

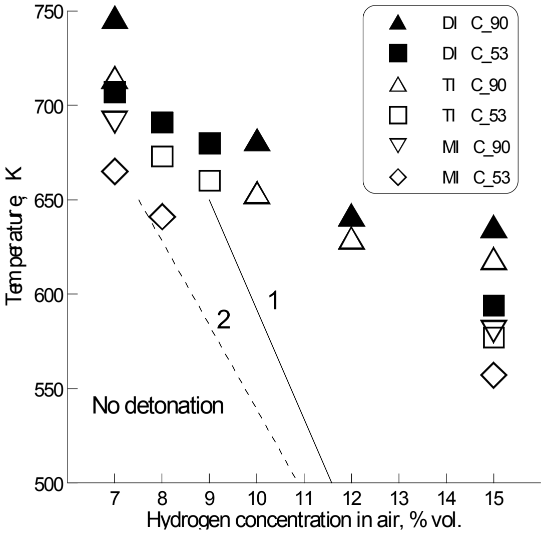

Fig. 2 Temperature – concentration diagram of detonability of lean hydrogen-air mixtures. Boundary detonation-no detonation:
1 – tube diameter 10 cm [3]
2 – tube diameter 27.3 cm [1].