Initiation of Hydrogen-Air Detonations at Nonuniform Conditions

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1 Introduction

The development of three-dimensional approaches for description of flow structure and energy release associated with a gaseous detonation are actual from theoretical point of view and practical applications, which have began to develop recently. The taking into account of three-dimensional phenomena and interactions is also extremely important under considerations of reacting flows accompanied with shock waves. In this work we have attempted to study initiation mechanisms of combustion and detonation at nonuniform flow and boundary conditions modeling the reaction behavior within the structure of hydrogen/air detonations for pressures 2 – 25 atm, temperatures of 850 –1850 K.

The flow inhomogeneities were produced by changing the geometry of reflecting wall at interactions with an incident shock wave of different intensities [1-3]. The measurements were compared with a reference data obtained behind normally reflected shock waves. Induction times and auto-ignition modes of the mixtures (strong, transient and weak) [4-6] were determined for wedge and conical walls of similar geometry. Particular attention has been paid in experiments to determining the critical ISW intensity required for initiation of different auto-ignition regimes.

2 Experimental setup

The used experimental configurations and drawings of the test sections are illustrated in Figure 1. Stainless steel shock tube of 76 mm in diameter were used in experiments. The length of the tubes is 5.5 m. The high-pressure valves with a forced electropneumatic start were used as high-pressure section. Mixtures were prepared by the method of partial pressures and kept for two days before use. Prior to the experiment, the tube was pumped out twice to the pressure of ~ 10^{-2} mm Hg. To lower a possible effect of parasite impurities, the tube was flushed with the test gas before the secondary pumping. The initial pressure of the mixture was controlled by pressure meter with accuracy of ± 0.3 mm Hg. Pressure variations in different cross-sections were recorded by piezoelectric pressure gauges with a 1.5-mm spatial resolution (Fig.1). The pressures at the cavity bottom were measured by high-frequency PCB pressure sensors Model 113A24 with rise time less than 1 μs. To fix the arrivals times

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of reaction front a set of ion current sensors was installed along the test volume upstream the reflecting cavity. Stainless steel test section was mated to the end flanges of shock tube.

To measure ignition times of reaction mixtures inside reflecting cavities, 5-mm transparent glass rods were passed through the models near the cavity bottom (Fig.1). The end face of the rods have been polished and coincided with profiles of reflecting surfaces. The glass rods provided a complete overview of the inner cavity and tube volumes. The flame emission in selected spectral band was registered by means of the photo-multiplier having the maximal sensitivity in the selected spectrum. For all shock wave focusing tests in hydrogen/air mixtures the luminosity of OH radicals (λ=306.5 nm) was detected using a narrow-band interferometric filter ($\Delta\ \lambda$ = 2 nm). Experimental results were recorded and processed by an automatic 10-bit data acquisition system and a central computer.

The identification of initiation modes was performed by comparing reflected shock wave velocities and post-reflected shock pressure at different distances from the cavity bottom. The additional ion probe measurements provided the data on reaction front propagation velocity. Gas parameters behind incident and reflected shock waves were computed by using shock adiabatic curve assuming the frozen chemistry and temperature dependence of heat capacity on the basis of shock wave velocity measurements at different locations along the tube. The Chapman-Jouguet detonation velocity V_{CJ} in preheated gas flow behind incident shock wave was calculated by means of laboratory developed thermochemical equilibrium computer code.

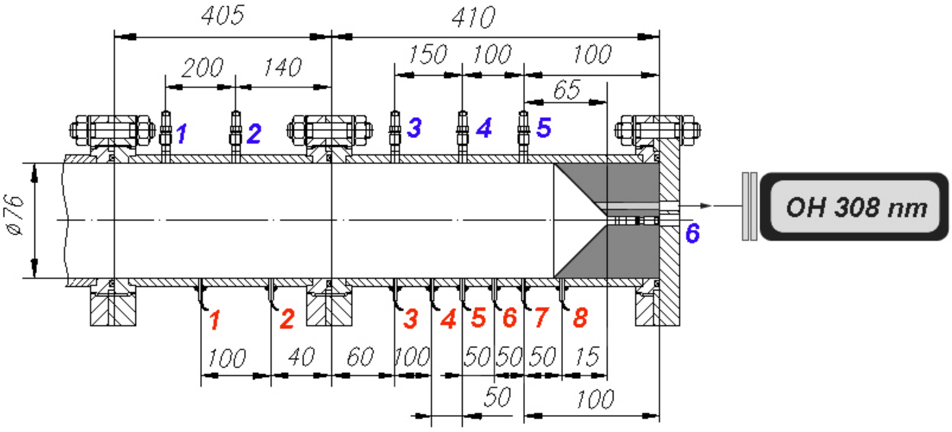

Figure 1. Drawing of the test section for shock wave focusing experiments in hydrogen/air mixtures. 1- 6 (blue) - high-frequency PCB pressure sensors; 2 - 1- 8 (red) – ion current sensors;

We have categorized different regimes of auto-ignition at focusing conditions in the following terms: weak ignition (deflagration), transient ignition resulting in DDT upstream the reflector apex and strong ignition (detonation). Particular attention has been paid to determine critical ISW intensity required for strong auto-ignitions of hydrogen-air mixture. The strong ignition mode corresponds to direct initiation of detonation in the vicinity of the reflector apex. The formed detonation propagates upstream the cavity bottom through the complex flow field behind the incident shock wave. The reflected wave velocity in this part of the tube was defined as V = W +u, where W is the visible velocity of reflected shock wave, and u is the flow velocity behind ISW. Visible velocity was calculated by processing shock-arrival times at pressure sensors located along the tube. If experimentally defined reflected shock wave velocity is compared with the calculated C-J velocity for temperature and pressure behind ISW, the direct detonation initiation occurs at shock wave focusing conditions.

There is a range of ISW Mach numbers in which transient modes of ignitions can be realized. The specific feature of this regime is the presence of powerful pressure spikes behind the reflected shock wave. The source of this overpressure is the localized explosion originating between reflected shock wave and the cavity bottom. This explosion is caused by collisions of bow shocks heading transverse flow structure behind reflected shock wave. These bow shocks are accompanied by flame and promote auto-ignitions.

If the intensity of the initiating center in the focusing region is low, and the mixture precondition at early stages of ISW reflection is not enough to support the acceleration of reflected shock–reaction zone complex, then weak mode of ignition occurs. The reaction zone lags the reflected shock wave. Small-scale turbulence as well as diffusive phenomena condition further combustion developments. In these cases, the visible velocity of reflected shock wave ***V*** is the same as for reflection in inert medium.

Figure 2 shows typical dependencies of the reflected shock wave velocity at different locations along the test section on the Mach number of the incident shock wave. It is evident from the graphs that, for self-ignition of the mixture, cone reflector are much more efficient. The critical Mach numbers required for direct initiation for cone reflection case were 2.75 at post-shock density of 0.1 kg/m^3, 2.29 at 0.4 kg/m^3, 2.01 at 0.73 kg/m^3, 1.96 at 1.392 kg/m^3, 1.94 at 1.86 kg/m^3, and 2.01 at 2.79 kg/m^3 respectively. In comparison the corresponding values for wedge reflection case were 2.32 at 0.73 kg/m^3, 2.29 at 1.37 kg/m^3, and 2.13 at 2.1 kg/m^3.

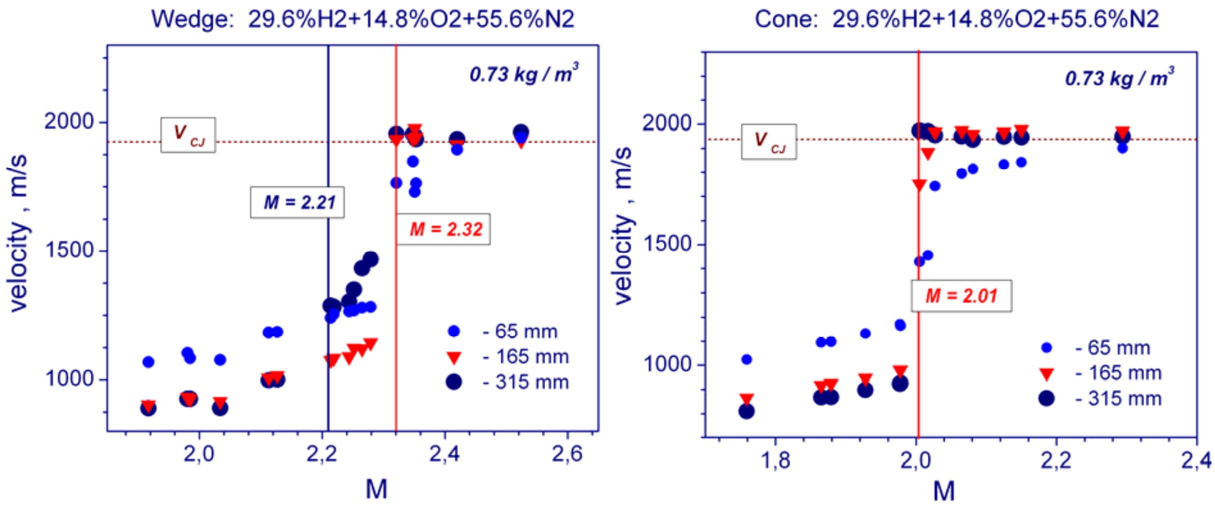

Figure 2. Absolute velocity of reflected shock wave propagating upstream the wedge (a) and cone (b) apex at different locations along the tube vs. ISW Mach number Red vertical line – the critical Mach number required for strong auto-ignitions; Navy vertical line- the critical Mach number required for transient auto-ignitions

3 Results

For normalized pressure–temperature plane P-T in stoichiometric Hydrogen/Air mixtures, Figures 3 presents positions of auto-ignition domain at shock-wave initiations in wedge and cone reflectors in comparison with a reference data obtained for plane reflection case. As is seen in the figure, the cone and wedge geometries result in the significant decreasing of mean post-shock temperature and pressure required for detonation initiations.

In comparison with a wedge reflection case at similar post-shock conditions cone reflections suppress significantly the occurrence of transient auto-ignitions. For wedge reflections the DDT upstream the reflector apex were detected at M = 2.21 - 2.32 for 0.73 kg/m^3, M = 2.17 - 2.29 at 1.37 kg/m^3. At higher densities experiments reveal only strong and weak auto-ignitions for cone and wedge reflection cases. In contrast to wedge initiations of detonation in stoichiometric Hydrogen/Air mixtures the cone reflections indicate the transient auto-ignitions only at low post-shock densities of 0.1 – 0.4 kg/m^3.

4 Conclusions

It was shown that the shock wave focusing in two-dimensional and axisymmetric profiles significantly decrease the ignition thresholds of the mixture as compared with the case of the normal reflection. For self-ignition of the mixture, axisymmetric reflectors are much more efficient than two-dimensional ones. Parametric diagrams, characterizing auto-ignition of hydrogen/air mixture at shock wave reflection from a plane wall, similar two-and axisymmetrical profiles show the significant influence of three-dimensional effects and interactions on the transformation local and integral regimes of combustion. It was demonstrated that in comparison with a normal reflection case the shock wave focusing can provide the auto-ignition of hydrogen at extremely low level of mean temperature of the mixture (≈ 500 K).

Acknowledgements

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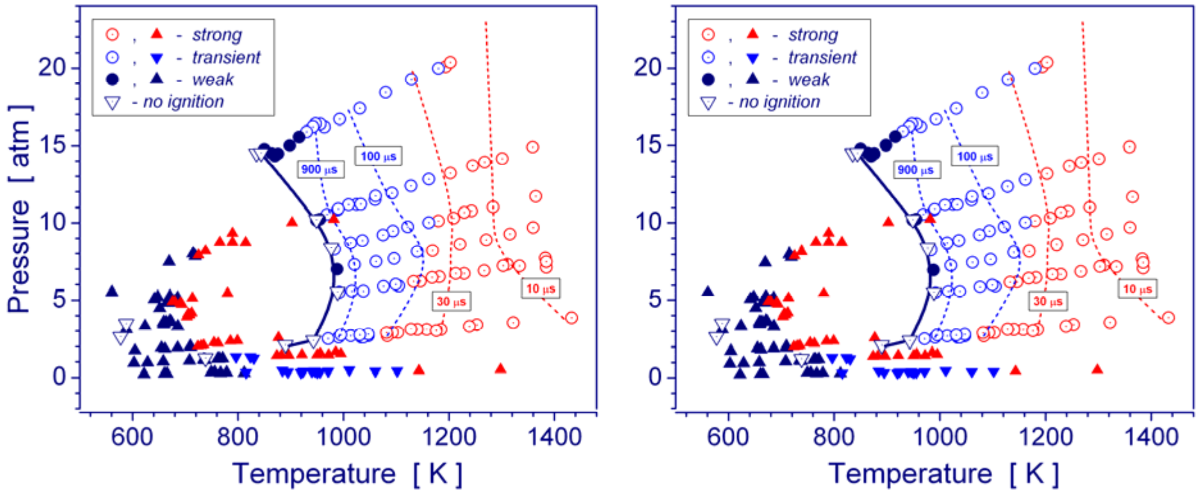

a) b)

Figure 3. Auto-ignition domains (strong, transient, weak and no ignition) of stoichiometric Hydrogen/Air mixtures in normalized Pressure –Temperature plane at shock wave reflections from plane wall, wedge (a) and cone (b) reflectors.

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