Auto-ignitions of Heavy Hydrocarbon Fuels at Shock Wave Initiation in Three-Dimensional Ducts

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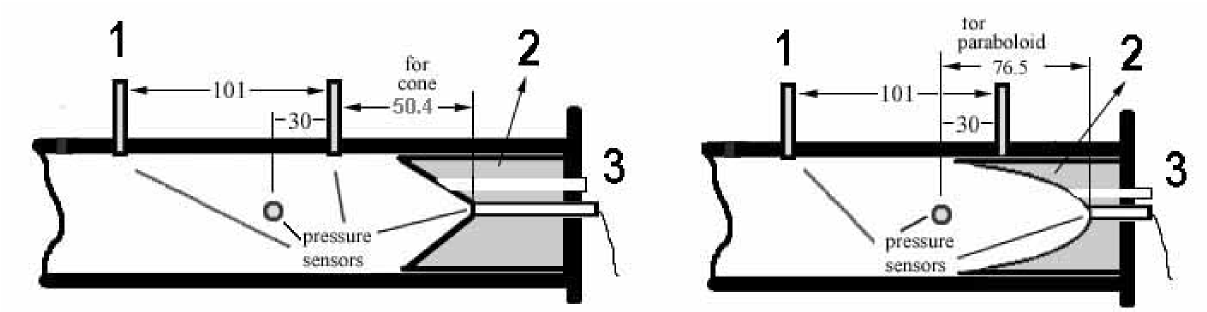
1 Introduction

For practical devices, initiation of combustion and subsequent propagation of reaction fronts usually take place when confinement walls are not smooth and plane. Thus, auto-ignition of the mixture occurs at non-uniform temperature and pressure distributions across the flow field caused by multiple interactions of different kinds of gasdynamic perturbations including shock waves. In these cases, the confinement geometry can facilitate substantially the mixture re-ignition inside the combustor due to shock focusing phenomena [1-5]. This work addresses to systematic experimental investigations of auto-ignition phenomena at shock wave reflections from axisymmetrical ducts in mixtures of heavy hydrocarbon fuels Jet-A and n-Decane with air.

2 Experimental setup

The stainless steel heated shock tube of 76 mm in diameter has been applied for these studies. The description of the setup is presented in [6]. Stainless steel reflectors for shock focusing were mounted to the end flange of the shock tube. On the basis of previous studies, three-dimensional cone (apex angle - 90^0) (Fig. 1a) and paraboloid (Shape - $Y = 0.051 \cdot X^2$) (Fig. 1b) have been chosen as the focusing elements having the best initiation properties in propane/air mixtures [7]. To measure ignition delays inside the cavities, 5-mm transparent quartz rods were passed through the models near the cavity bottom (Fig. 1). The end sides of the rods have been polished and coincided with profiles of reflecting surfaces. The rods provided a complete overview of the gas volume near the tube axis. The flame emission in selected spectral band was registered by means of the photo-multiplier having a maximal sensitivity in the selected spectrum. In all experimental runs the luminosity of C_2 (λ=516.5 nm) was detected by using a narrow-band interferometric filter ($\Delta \lambda$ = 8 nm). The ignition delay time was defined as the time difference between the appearance of reflected shock wave at the cavity bottom and the beginning of emission intensity growth (Fig. 2).

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 thermodynamic properties of Jet-A and decane were taken from the work [8]. Lean, stoichiometric and enriched Jet-A and stoichiometric decane/air mixtures were investigated in this work.



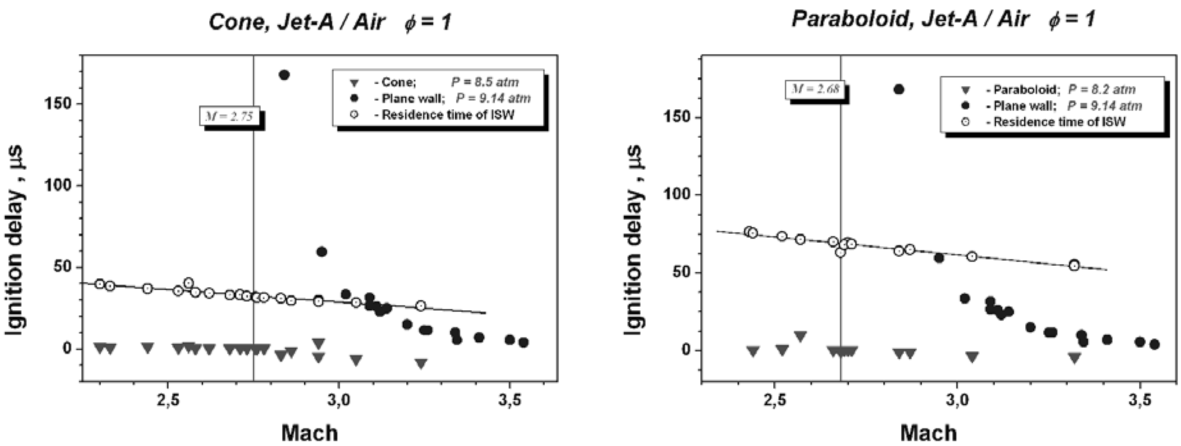
a) b)

Fig. 1. Schematic of the test sections for auto-ignition studies in Jet-A/Decane/Air mixtures at shock wave focusing. 1 – pressure sensors; 2 – cone (a) and paraboloidal (b) axisymmetrical reflectors; 3 – 5-mm transparent quartz rod

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) [9,10]. Particular attention has been paid to determine critical ISW intensity required for strong auto-ignitions of Jet-A and decane. 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.

Usually, 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. Usually, the



a) b)

Fig. 2. Ignition time of Jet-A/Air mixture vs. ISW intensity at shock wave focusing in a cone (a), paraboloid (b) and behind normally reflected SW at equivalent mean post-shock pressures. Open circles correspond to the residence time of ISW in a reflector before the reflection from the apex.

onset of detonations can arise at the tube axis or at the walls due to collisions of bow shocks to each other and tube wall [3,4]. This initiation mode is an example of DDT under shock wave focusing.

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 the weak mode of ignition occurs. The reaction zone lags the reflected shock wave. Small-scale turbulence as well as diffusive phenomena governs further combustion developments. In these cases, the visible velocity of reflected shock wave V is the same as for reflection in inert medium.

3 Results

It was shown that in contrary to propane/air mixture, the shock wave focusing in cone and paraboloid in Jet-A initiates supersonic deflagrations propagating upstream the reflector apex. The subsequent transition to detonation occurs at the distance of 60 – 80 mm from the cavity bottom. Shock wave initiations in paraboloid at high pressures was more effective for initiation of detonation in Jet-A/Air mixtures. The best initiation has been obtained in lean Jet-A/Air mixture (ϕ = 0.8). In this case, the critical Mach number required detonation initiation was M = 2.27. Coresponding results in in stoichiometric Jet-A/Air mixture (ϕ = 1.0) was equal to M = 2.49 (Fig. 3).

Rich and stoichiometric mixtures exhibit the best initiation properties in a cone reflector with apex angle of 90^0. The critical Mach numbers required for detonation initiation in a cone were equal to M= 2.49 and M=2.48, respectively.

The best initiation has been obtained in stoichiometric n-Decane /Air mixture. In this case, the critical Mach number required detonation initiation in paraboloid was M = 2.08 (Fig.3).It was shown that in comparison with simple representative fuels (propane, n-Decane), a great reaction time of Jet-A has a negative influence on direct initiation of detonations at shock wave focusing.One component heavy hydrocarbon fuel like n-Decane with a simple reaction paths show better initiation properties and is more suitable for PDE applications.

Acknowledgements

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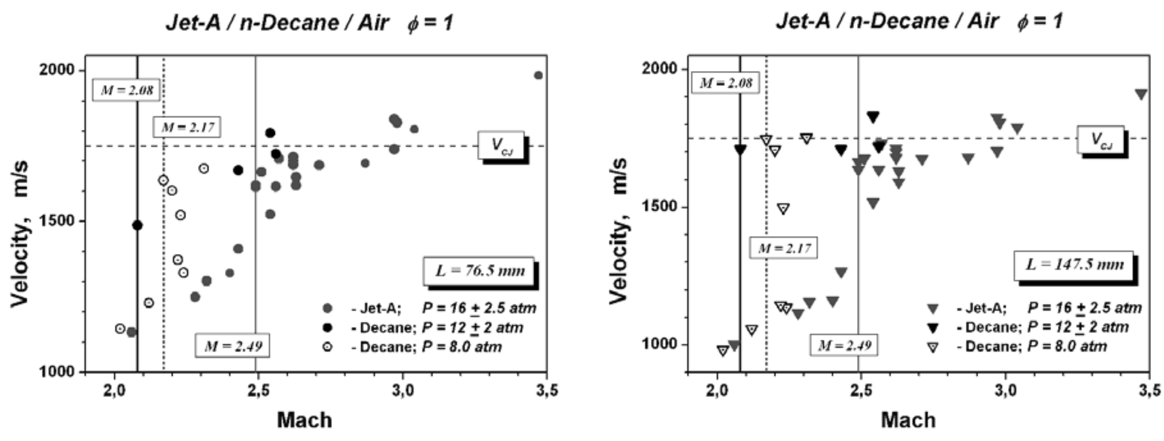

a) b)

Fig. 3. Absolute velocities of reflected shock wave in stoichiometric Jet-A and n-Decane/Air mixtures in paraboloid vs. ISW Mach number at distances 76.5 mm (a) and 147.5 mm (b) from the cavity apex.

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